FASHIONABLE BCI: APPLYING A USER-CENTERED DESIGN APPROACH TO DEVELOPING A SOCIALLY ACCEPTABLE BRAIN-COMPUTER INTERFACE DEVICE FOR WOMEN

By

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To my grandparents, Francine and Eugene McMillan who enabled me to make all my dreams come true

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LIST OF ABBREVIATIONS

ALS	Amyotrophic Lateral Sclerosis
BCI	Brain-Computer Interface
CNS	Central Nervous System
CRS	Comfort Rating Scale
e-textiles	Electronic Textiles
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
HCI	Human-Computer Interaction
ISO	International Organization For Standardization
LSL	Lab Streaming Layer
MIT	Massachusetts Institute Of Technology
QS	Quantified-Self
UCD	User-Centered Design
UX	User-Experience
WEAR	Wearable Acceptability Rating

Abstract of Dissertation Presented to the Graduate School
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The Brain Computer Interface (BCI) field has been around since the 1970s but has yet to reach mass commercial success or mass adoption beyond the medical community. There are several factors attributing to BCI's lack of pervasiveness including a lack of consideration for user-experience and usability. Initially the technology was used in the medical field to assist patients with various impairments related to spinal cord injury, stroke, neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS), and neurodevelopmental disorders such as spinal muscular atrophy or cerebral palsy. An increase in the number of non-invasive wearable BCI devices has led to more interest in non-medical applications of the technology for a wider range of consumers. Even with the surge of new devices, BCI has yet to reach wide spread acceptance. Although there are several examples of wearables that have failed, some are more popular and socially acceptable than others.

Current wearable trends show that the most popular wearables from 2014-2015 were accessories or jewelry items and were targeted largely at a female audience. However, women sometimes have increased difficulty using wearable BCI devices in

part due to hair length, texture, and density. This work sought to investigate the barriers impeding women from utilizing BCI technology as well as gain insights into the design trade-offs and characteristics of a socially acceptable BCI device for women. A user-centered design (UCD) process was used to design three fashion accessories that are capable of sensing EEG and serve as the first wearable BCI devices designed specifically for women.

Three BCI prototypes were created that outperformed an existing device on all usability metrics and a set of 32 characteristics of socially acceptable BCI devices was created. Therefore the goals of this project were achieved through a mixed method approach.

CHAPTER 1
INTRODUCTION

Between 2008 and 2009 there was a surge in the introduction of consumer grade BCI technology. Brunner et al. (2011) refers to commercial BCIs for consumer products as devices that measure and translate brain signals into output that provides value to the user. These early devices include the Neurosky Mindset and Mindwave as well as the Emotiv EPOC. These devices took the EEG sensing technology traditionally found in non-invasive electrode caps and placed it in a more wearable headset with the aim of increasing BCI usage amongst consumers. Although the first consumer BCI headsets were introduced just short of a decade ago, their usage and popularity has not been widespread. There are several barriers hindering BCI from becoming more pervasive. The lacks of consideration for usability and user experience are two examples of the barriers (Lightbody et al., 2014). This lack of consideration translates into devices that are functional but not socially acceptable.

This work sought to explore the characteristics of a socially acceptable BCI device and used the insights gathered to influence the design of three device prototypes. Acceptability of wearables differs from general technology acceptance because additional factors such as style, dress and fashion must be considered (Kelly and Gilbert, 2016; Adam and Galinsky, 2012). Therefore, two scales created specifically for wearable evaluation were used to assess existing devices and to make comparisons to the newly designed prototypes. The WEAR Scale developed by Norene Kelly, was the first standardized metric created to measure the socially acceptability of wearables. Wearable social acceptability can be defined by if a user is willing to wear a device and considers it acceptable for others to wear a device (Kelly and Gilbert, 2016).

Although, some work has been done to evaluate existing BCI devices, there are still gaps in this research leaving the need for more work to be done. Currently devices are mainly evaluated for performance and accuracy. Human factors such as comfort, aesthetic, and social acceptability are rarely considered (Motti and Caine, 2014; Gürkök and Nijholt, 2012). This work sought to investigate some of the more human factors affecting BCI and it's social acceptability while using those considerations to design and evaluate new more acceptable prototypes.

Motivation: BCI devices can be used in several contexts from gaming to communication. Data provided by consumer EEG devices can be used to offer feedback to users in quantified self-applications as well as HCI researchers using a device as a UX research tool. Not only does hair texture and density prohibit some users (mostly women) from being able to participate in some BCI studies, it also prevents them from benefiting from activities such as neurofeedback provided by BCI applications (Saab et al., 2011; Ekandem et al., 2012). As the field of BCI continues to grow and the number of applications expands, everyone should have equal opportunity to benefit from this cutting edge technology.

The most fundamental goal of this research is to make BCI more pervasive, specifically for women. The literature suggests that two major impedances preventing an increase in pervasion from happening is the lack of usability and user experience consideration in the field (Lightbody et al., 2014). Most of the current evaluation methods focus on performance metrics with little usability or UX evaluation (Lightbody et al., 2014). The community suggests that more work needs to be done in this area to increase BCI usage and user acceptance (Bos et al., 2010; Bos et al., 2011).

In 2015 women made up 54% of the owners of activity trackers (NPD Group, 2015). This indicates that women have an interest in quantified-self (QS) tools. BCI can also be used as a QS tool that unobtrusively allows women to track their cognitive activity. If BCI is to become as ubiquitous as the current activity trackers, they must be socially acceptable and address some of the barriers currently limiting women's use of the devices. There have been cases where researchers have had to exclude female subjects interested in participating in BCI studies because the devices being used did not work with their hair texture and density (Ekandem et al., 2012). Women often experience longer setup times or an inability to capture a strong signal due to poor sensor to scalp connections. Some of the known barriers inhibiting women from more widespread BCI usage are; hair texture and density, current device aesthetics, and discomfort overtime with current devices. Targeting these barriers will help to improve the usability of wearable BCI amongst women (Norman, 2005; Tractinsky et al., 2000).

The goal of this work is to design a usable fashion accessory that is capable of sensing EEG, allowing women to unobtrusively track their cognitive activity by addressing current barriers. By applying a user-centered design process to the development of three device prototypes, this work is able to provide the research community with a comparative analysis of newer BCI devices as well as target specifications and a set of characteristics for socially acceptable BCI. These specifications and characteristics can be used to influence future designs. Finally, an exploration of design tradeoffs and considerations for BCI devices will be provided for the community.

CHAPTER 2
RELATED WORK

2.1 Brain-Computer Interface

Jacques Vidal first introduced the field of Brain-Computer Interface in 1970 (Vidal, 1973). A brain-computer interface measures brain activity, which translates into an artificial output that replaces, restores, enhances, supplements or improves the natural central nervous system (CNS) output. As a result, the interaction between the CNS and its external or internal environment is changed (NPD Group, 2015). Fields like neuroscience, cognitive psychology, psychophysiology, and others have historically contributed towards the understanding of how the brain functions. Subsequently, researchers from these fields have also been contributing to the BCI field for decades. The use of BCI first began within the medical community, but in recent years the field has expanded to non-medical research areas as well (NPD Group, 2015; Ekandem et al., 2012; Norman, 2005). The recent increase in non-invasive wireless BCI electroencephalographic (EEG) devices has influenced this recent expansion.

Although, much is still unknown about the brain, researchers have begun to apply what is known about it in non-medical areas. This expansion has led to the inclusion of BCI in the Human-Computer Interaction (HCI) research field. The current wearable non-invasive consumer grade BCIs are mainly used by researchers and developers. The purpose of these devices is to be used by both people with disabilities and more recently people without disabilities. In HCI, one focus is to develop applications to assist non-disabled users in their daily activities and to understand user's behaviors while they perform various tasks (Tractinsky et al., 2000). Research in this area covers a wide range of applications ranging from systems that adapt to users'

affective state to tools used to evaluate interfaces (Ekandem et al., 2012). Much of this research features passive BCI systems. This is one of the three categories of BCI. The other two categories, active and reactive, involve the user consciously trying to control an application, while the brain activity output in the latter is in reaction to an external stimulus (Zander and Kothe, 2011).

Passive BCI systems however, generate output from brain activity without the purpose of direct control (Zander and Kothe, 2011). Previous studies have shown that this method can classify mental workload during HCI usability tests with up to 99% accuracy (Gimes et al., 2008). This method has also been used to measure affective states such as engagement (Andujar et al., 2013; Szafir and Mutlu, 2012). Often these studies or applications require users to wear BCI devices for long periods of time.

A BCI device's comfort level may impact user acceptance amongst consumers or subjects in research studies (Ekandem et al., 2012; Mayaud et al., 2013; Hairston et al., 2014; Nijboer et al., 2015). Much of the BCI research previously done utilizes hardware that features a cap design for brain signal acquisition. Many medical grade caps have a large amount of wires, as seen on the g.Sahara cap in Figure 2-1 (g.Tec, 2012). These caps can limit the user's mobility, and are not visually appealing. Advances in technology have made it possible to design BCI devices that are more aesthetically pleasing (Quek et al. 2013). The degree to which a BCI device is fashionable or aesthetically appealing could influence its success in a larger, mainstream, consumer market (Tractinsky et al., 2000; Norman, 2005).

Although initially BCI technology was intended for the medical community, its popularity is growing amongst healthy users. Van Erp et al. (2012) suggest that in the

future BCI user-state monitoring will have a high societal impact because it will help promote a healthy lifestyle and safe transportation. However, to become a viable interaction modality for everyone, user-experience and usability have to be considered when designing devices, systems, and applications.

Non-invasive BCI headsets are considered to be a member of the wearables family just like smart watches and fitness trackers, yet they have not seen the same level of acceptance. Some of the issues may be attributed to a general lack of knowledge about BCI and what it can be used to do. Users have to feel that by using a BCI as an interaction modality or personal informatics wearable, they are enhancing their user-experience (Bos et al., 2010). For others who know about BCI, their lack of interest could be a result of the devices' level of social acceptability, comfort, aesthetic or performance capabilities. Figure 2-2 illustrates a few wearable non-invasive BCI devices. This research explored how users felt about current devices and what was keeping them from more widespread usage. Additionally, the research used focus groups to determine the same user group's general opinions on wearable technology and other existing wearable devices.

Figure 2-1. g.Sahara EEG cap by g.Tec.[1]

[1] Source: http://www.gtec.at/Products/Electrodes-and-Sensors/g.SAHARA-Specs-Features

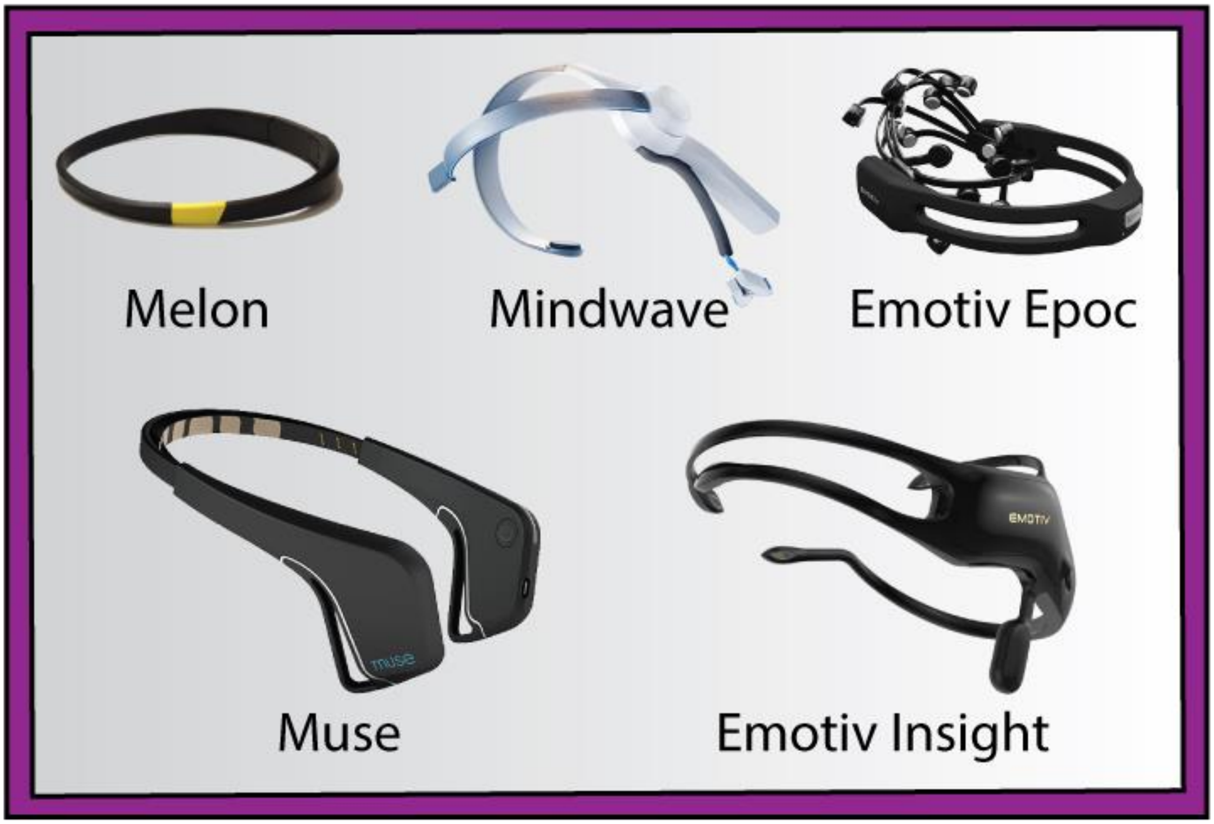

Figure 2-2. Wearable non-invasive BCI devices

2.2 Wearable Technology

Wearable technology or wearables are defined as electronics or computers that are integrated into clothing and accessories that can be worn comfortably on the body (Michael, 2014). A few examples of wearables can be seen in Figure 2-3. These include smart watches, fitness trackers, smart clothing, intelligent jewelry such as bracelets with embedded sensors, and BCI devices.

Figure 2-3. Examples of wearable technology

The first battery-run, mobile, wearable was created in 1961 by Edward O. Thorp and Claude Shannon (Thorp, 1998). Thorp's article, “The Invention of the First Wearable Computer” details the design and construction of the roulette- predicting device. The initial device was the size of a cigarette pack, utilized 12 transistors and was hidden in a shoe. Thorp validated this device by testing it in a Las Vegas casino. In 1966 the device was publicly announced and by the 1970s an upgraded version known as the Eudaemon Shoe, seen in Figure 2-4, was built by a small group of scientists (Thorp, 1998).

Figure 2-4. Eudaemon shoe[2]

The 70s also brought on other early examples of wearables, such as the Walkman, but it was not until the late 1980s to early 1990s that wearable technology began to formally emerge in research labs such as the Massachusetts Institute of Technology (MIT) Media Lab (Ryan, 2014). During this time Steve Mann created the field of “wearable computing” while in graduate school at MIT. He defined a wearable computer as a user controlled computer that is always on and accessible while being incorporated into it’s user’s personal space (Mann, 1998).

In 1997, Mann suggested that as the development of wearables continued, apparatuses would become invisible as they disappear into ordinary clothing and

[2] Source:http://physics.ucsc.edu/people/eudaemons/layout.html

eyeglasses (Mann, 1997). The fruition of this prediction could be seen coming to life with the development of Google Glass and the Under Armor biometric compression shirt seen in Figure 2-3. The desire to make wearable technology fashionable has led to increased interest in making computers disappear into clothing. This in turn led to more research into conductive and flexible textiles as well as embedding small components directly into textiles. Small transistors make embedded textiles possible. As microprocessors continue to shrink in accordance with Moore's Law (Moore, 1965), wearable technology becomes more powerful and more invisible. Other factors that have contributed to the advancement of wearables include smaller batteries and the miniaturization of cellular technologies such as WIFI, Bluetooth and RFID (Seymour and Beloff, 2008).

2.2.1 Fashionable Technology

As the technology enabling wearables continues to become more advance, and their usage is more pervasive, fashion is becoming a larger factor. Steve Mann offered one alternative to wearables being unobtrusive and hidden; that they be sleek and fashionable (Mann, 2002). Sonny Vu, founder of Misfit Wearables, echoed that sentiment stating that wearables need to either be gorgeous or invisible (Wasik, 2013). The Google Smart Jacket in Figure 2-5 was a collaboration with Levi Strauss that sought to balance fashion with hidden technology ("Project Jacquard", n.d.). Although the jacket allows cyclist to access their phone's features, it looks like a standard Levi's denim jacket on the outside. Not all wearables can be as hidden as the technology in the Google jacket, so the goal is to make devices that at least represent technology people want to display on their bodies, as fashion (Wasik, 2013).

Figure 2-5. Google smart jacket[3]

The term Fashionable Technology was introduced by Sabine Seymour. She describes it as considering "end users as fashionable beings, attentive to style, aesthetics, branding, and the expressive potential of wearable technologies" (Seymour and Beloff, 2008). The fashionable technology perspective focuses just as much on the human factors aspects of the technology as it does on the functionality of the technology. It is the intersection of aesthetics and function in regard to the use of technology (Seymour and Beloff, 2008). One of the first examples of an haute couture (high fashion) brand using technology on a model to communicate an experience is the airplane dress (Chalayan, 2000) from the Hussein Chalayan spring/summer collection in 2000. The dress, seen in Figure 2-6, was made with airplane construction material and changed shape using a remote control.

[3] Source: https://atap.google.com/jacquard/

As interest grew in the fashion technology domain, designers began to utilize bags and accessories as a means of concealing the technical components needed to make their visions come to fruition (Seymour and Beloff, 2008). A very literal example of this can be seen in Figure 2-7 with the Ralph Lauren charger bag (Meinhold, 2014). The iconic Ricky bag has built in LED lights and a battery for charging electronics. In addition to handbags, another important component that allows the technology to be hidden is when the fabric is the technology.

Electronic textiles (e-textiles) are materials that use biometric or external sensors, wireless communication, power transmission and other interconnection technology to network computational devices together within fabric (Berzowska, 2005). E-textiles, sensors, micro-controllers, and embedded systems in general often play a major role in enabling the functionality of fashionable technology projects. Steve Mann, also stated that many of his early inventions did not put people at ease due to their obtrusiveness. As his devices began to shrink in size and people’s attitudes toward personal electronics began to shift, he noticed an increase in social acceptance (Mann, 1997).

Figure 2-6. Hussein Chalayan airplane dress from spring/summer collection 2000[4]

[4] Source: https://www.metmuseum.org/toah/works-of-art/2006.251a-c/

Figure 2-7. Ralph Lauren charger bag[5]

2.2.2 Social Acceptability

Social aspects and user acceptance have traditionally been areas of concern in wearable computing. Sabine Seymour believes that garments are a direct interface between people and their environment and can be used to transmit and receive messages, emotions, and experiences (Mann, 1997). Wearables are more than just enhanced gadgets; they are also communicators of style and send social messages. If user acceptance is to remain high, the communicated message should to be something the wearer is happy with (Wasik, 2013).

[5] Source: https://inhabitat.com/ecouterre/ralph-laurens-5000-ricky-bag-comes-with-built-in-phone-charger/

Wearable literature list two popular principles that address the social messages created by wearables; the Bluedouche Principle and the Trucker Hat Principle (Wasik, 2013). The Bluedouche Principle references the stigma associated with people who wore Bluetooth devices (Figure 2-8), when they were first introduced around the year 2007 (Shaw, 2011). People were seen as superfluous, too eager to answer a phone call and too readily available. Wearing a Bluetooth did not send a positive social message or the intended message. The Trucker Hat Principle presents the argument that people have a desire for individuality and uniqueness. It is a reference to a time when trucker hats were cool until everyone started wearing them and they were no longer considered cool. The message devices send about the wearer is important and cannot be disregarded when considering new designs.

Figure 2-8. Bluetooth headset[6]

[6] Source: https://www.networkworld.com/article/2228495/smartphones/it-s-official--wearing-a-bluetooth-headset-makes-you-ugly.html

Many wearables are designed to appeal to people that are engaged with technology and have little regard for personal, generational and cultural factors. Companies like Ringly who have considered those factors are praised by accessory designers and fashionistas but criticized by technology reviewers because they reduce the amount of features to improve the appearance (Silina and Haddadi, 2015). This is a primary example of how fashion designers and fashion industry insiders have a different perspective from engineers. “Fashion designers know how to make items that are not only fitted for the human body but that are also beautiful and desired by consumers” (Ferraro, 2011). Similarly, the human body should be a point of inspiration and a stimulus for wearable designers. Wearability is an important concept to consider when designing wearables. It is the interaction between the body and the wearable object. Note that dynamic wearability extents that definition to include the body in motion (Gemperle, 1998).

If wearables are going to be successful, they need to leverage fashion designers' expertise and perspective (Juhlin, 2015). For example, fashionable people use fashion logic/rules such as what is “in” and what is “matching” to pick out clothing items that make outfits. Juhlin and Zhang, authors of Digitizing Fashion propose “outfit-centric” wearables that make wearable devices components of outfits that adapt to style changes (Juhlin, 2015). Researchers have reported an emerging trend where wearables are becoming high tech functioning devices that are designed to look more like fashion accessories (Wright and Keith, 2014). This can be seen with the Intel MICA and Misfit Swarovski Activity Crystal, pictured in Figure 2-9 and Figure 2-10 (Braddock, 2015; Misfit, n.d.). Misfit creator Sonny Vu, said that many of the wearable devices on

the market “look like they were made by Silicon Valley men for Silicon Valley men,” because they are made from rubber and plastic. He felt the devices were more suited for utilitarian gadgets than stylish accessories. When asked what he thought of this emerging world of wearables he said "it would never arrive if nobody consents to wearing them" (Wasik, 2013).

Figure 2-9. MICA smart bracelet from Intel and Opening Ceremony[7]

[7] Source: http://www.businessinsider.com/best-wearable-tech-for-women-2014-9

Figure 2-10. Misfit Swarovski activity crystal[8]

2.2.3 Barriers To Success

Although knowledge and awareness of wearables have increased since the 1990s, the majority of the wearables that have come to market have failed commercially (Ryan, 2014). There is a general consensus that the causes of the low adoption rates are ongoing issues surrounding data interpretation, business models, novel interfaces, battery consumption and miniaturization of component (Mortier et al., 2014; Silina and Haddadi, 2015; Starner, 2001). Lucy Dunne identified four design barriers inhibiting wearables from commercial success: functionality, manufacture, developmental practice, and consumer acceptance (Dunne, 2010). A few of these barriers will be discussed in detail below.

[8] Source: https://misfit.com/fitness-trackers/swarovski-activity-crystal

The barriers to functionality were characterized by three aspects; wearable sensing, interaction, and power requirements. Sensor accuracy and reliability have always been barriers for wearables because noise is often introduced due to the mechanical coupling of the sensors with the body and the contact between the sensors with the skin. These issues can be especially problematic with BCI devices. Researchers have found that there is often a tradeoff between signal quality and human comfort, where quality usually wins (Dunne and Smyth 2007). Interaction can also require a tradeoff between user comfort and performance. Attempting to make traditional interaction techniques (ex. keyboard input on a worn garnet) more comfortable can decrease functionality. Although keyboards work best with rigid components, it can be uncomfortable to wear hard, rigid components. Additionally, power is a significant issue when it comes to wearables. Although approaches such as solar and kinetic power have begun to be investigated, more research needs to be done.

The barriers to manufacture were characterized by three aspects; integration of textile and electronic components, durability and flexibility, and coordination/training of manufacturers. Similar to the comfort/accuracy tradeoff in wearable sensing, the durability/flexibility tradeoff is important in manufacture. Dunne (2010) only reports two aspects contributing to the barriers of developmental practice; product development/use cycles and cultural barriers. The major issue with developmental practice is that wearable technology requires collaboration between two fields that do not know much about each other, creating significant cultural barriers. The logistics, training, product development, traditions and design approach used by each industry often clash during

the development of wearables. To successfully create integrated wearable applications a deep understanding of the apparel and technological components as well as the associated techniques for manufacture must be achieved.

Finally there are two main barriers to consumer acceptance according to Dunne (2010). Those barriers involve ‘functionality and use’ and ‘identity and aesthetics’. She reports that there is often an issue of functionality mismatch. This occurs when a function is given to a garment but is better suited for mobile devices or better worn as an accessory as opposed to a garment. Additionally, device implementation often affects the attractiveness. The comfort requirements and constraints for clothing are more rigorous than traditional mobile devices.

Traditionally the needs of the device supersede the needs of the user and the result is a wearable that is more durable but not as comfortably or aesthetically pleasing. It can be concluded that worn devices say more about a user than carried devices. A worn artifact has a larger impact on a wearer’s identity by influencing body image, societal roles and perceived social status in the same way that clothing does (Adam and Galinsky, 2012; Dunne, 2010). In order to create successful wearable technology, designers must consider fashion trends as well as technology trends (Dunne, 2010).

A survey published in 2016 analyzed the historical and current trends of wearable technology (Berglund et al., 2016). They found three distinct growth periods in the past: 1980s to 1997, 1998-2000, and 2001-2004. The first period was technology-driven and focused on wearable computing applications such as the early projects by Steve Mann. The second period consisted of the fashion and textile industry integrating

technology into garments such as the Hussein Chalayan airplane gown previously discussed. The third period moved toward smart clothing for a more commercial audience. In addition to historical trends, current trends beginning in 2014 were analyzed. They found that emphasis has shifted away from garments towards jewelry and accessories. This is thought to be attributed to a decrease in size and power consumption of wearable enabling hardware. The increased popularity of the jewelry and accessory form factors may be responsible for the shift in target audience. From 2013-2014, 74% of the wearables on the market were intended for a unisex audience. By 2015 around 66% of the products on the market were targeted specifically at women, a big jump from the 14% the previous year (Berglund et al., 2016). Wearable design guidelines and consumer trend reports can be used to influence the development of new BCI devices.

There are two key takeaways that relate to BCI devices. The first takeaway is the form factor. Based on the information reviewed in this section, aesthetics and social acceptability are important aspects of wearable design. The 2016 survey suggests the wearable technology field is moving towards devices that have beautifully designed jewelry or accessory-like form factors (Berglund et al., 2016). This is not in line with the appearance of the current devices on the market. The second takeaway is the target audience. The trend report suggests that women have become major targets for wearable technology, yet this user group has the most difficulty wearing the current BCI devices. The goal of this research was to prototype a new BCI device that is designed for a female target audience with the intention of being a fashion accessory.

2.3 Wearable BCI

As previously mentioned, BCI began in the medical community but recent years has seen an increase in the investigation of non-medical applications. This has lead to an increase in the number of wireless wearable BCI devices. Similarly, as microprocessors and mobile technology such as Bluetooth LE have continued to advance, an interest in all wearable technology continues to propagate. Because many of the current wearables have been met with limited or short lived commercial success, researchers and tech experts have begun to investigate design guidelines for wearable technology. Although there is no standard set of guidelines agreed upon by the wearable community, I have aggregated a list of some of the published suggested guidelines (Kitagawa, 2014; Rao, 2016; Razvan, 2015; Sethumadhavan, 2018; Stern, n.d.; Stinson, 2015). This section summarizes the guidelines, how they can be applied to BCI design and how well BCI is or is not currently implementing each guideline.

Many of the guidelines do not translate well to BCI because they focus on user-interface suggestions. Currently, BCI devices do not contain output displays or graphical user interfaces on the device itself. A list of 32 items was aggregated to form the cursory list in Table 2-1.

Table 2-1. Aggregated List of Wearable Design Guidelines.

Number	Guideline
1	Augment, don’t replicate
2	Design, don’t reuse
3	One size does not fit all
4	Think always on, think low power
5	Security above all
6	Build a viable ecosystem
7	Get the price right
8	Make it usable
9	Stick to the core features
10	View wearables as device accessories
11	Does it pass the “turn around” test
12	Create insights, not data
13	Beautiful or Invisible. But not in between
14	A wearable isn’t necessarily something you wear all the time
15	Tell a story. Because it’s always about the story
16	Keep It Glanceable
17	Don’t Look Now
18	Avoid the Data Avalanche
19	Balancing Public and Personal
20	Design for Offline
21	Design – It’s Important!
22	One Size – Not the Ideal Solution
23	Optimize Compatibility With The Platform
24	Security Requirements
25	Think Out Of the Box
26	Enable Power Optimization
27	Keep Minimalistic Intrusion
28	Ensure Enough Predictability
29	Design for trust
30	Provide personalized motivation
31	Enable wearability
32	Use tactile interaction wisely

There was some redundancy among the items. Ten themes emerged from the aggregated list.

1. Wearable specific design choice – The guidelines warn against simply putting a mobile OS on a watch interface. The watch interface has its own set of nuances that have to be considered. Additionally, what works for one wearable may not be appropriate for a different type of wearable. Design decisions that are appropriate for a watch may not be appropriate for head worn wearables. BCI devices do not

currently have visual on device interfaces for users to interact with. Therefore many of the guidelines, including some on this list, do not apply to BCI design.

2. Power optimization – Several sources indicated that power consumption is an important consideration. No specific battery life was suggested, but low power and quick charge were general guidelines. Currently the Muse device has a battery life of 5 hours and the Insight has a battery life of 4 hours. Four hours is not a long time, if a student is using it during class all day. Even if they were to turn the device off between classes, 4 hours could equate to only two classes. A charging case that doubles as storage and transport could be a solution.

3. Privacy and Security – Not only do wearable devices collect personal health information that people may want to keep private or have control over where it is stored, but they can also communicate information to users that is personal. The guidelines suggest that the most private setting always be the default. Trust was also an issue that was mentioned. Attributes that affect trust are consistency, honesty, and transparency. Trust can be difficult to gain from new BCI users. It can be difficult for most people to understand how a BCI device is capturing raw EEG and once the barrier is removed, if they are not trained to interpret EEG data, they would not be able to verify the data they are viewing.

4. Usability – Seven guidelines were themed as usability issues. In general the usability guidelines were mostly related to user interface usability, which BCI devices do not have. However, the usability of current devices, particularly for women was the motivation for this research. Based on the findings from related work, this is an area that BCI devices need to improve.

5. Create compelling usages – One open challenge in the BCI research community is the need for a killer app. Focus group participants mentioned thinking BCI was cool, but not understanding what they would use it for on a regular basis with what's currently available. Many of the use cases discussed in the focus group do not currently exist. The guidelines suggest that devices should offer so much value to the user that they would turn around to return home if they forgot it. The guidelines also suggest that wearables offer personalized feedback. Currently, many of the devices on the market are difficult to use by non-programmers and do not come with meaning applications for everyday use. The Muse device has an application that is ready to use for meditation and does a good job of adhering to this guideline.

6. Meaningful Insights – Multiple guidelines indicated the importance of providing users with meaningful insights and not just data. This is especially important for BCI, because raw EEG data can be impossible to interpret to an untrained eye. Aside from simply looking cool, users would get very little value from their raw EEG data alone. It is imperative that any BCI software that accompanies the device translates the data into meaningful insights. The Muse device is the best example of this right now. It's mediation app is simple, easy to use and intuitive. The software that comes with the Emotiv devices is not as user-friendly for

novice, non-technical users. Some devices do not come with much software aside from a simple graphical user interface that indicates if the device is connected and displays the raw EEG. The are intended for researchers with the technical ability to interpret and translate the data.

7. Aesthetic Design- The aesthetic guidelines suggest that wearables should be minimalistic and non-intrusive. The alternative to having a minimal and invisible design is having a beautiful design. The newest class of wearable BCI devices attempt to take design into consideration. Designers continue to push the envelope as they move further away from the electrode cap design. However, research, including this project, shows that the current devices are not socially acceptable and better designs still need to be achieved. Therefore, this is another guideline that BCI is struggling follow. The need to improve the aesthetic design was also a motivation for this work.

8. Usage – The guidelines emphasize the importance of understanding when, how, and how often a wearable will be used when making design decisions. Because a killer app has yet to be created for BCI, there is still lots of ambiguity around what people would ideally be using their device for and when. Based on the focus groups and feedback during user studies, it was discovered that women were particularly interested in the education context and personal informatics in general. They were more interested in improving productivity through affective monitoring during class or work scenarios. This means they would wear the devices at their desk or in class mostly. That could have implications on how the device needs to look and how easily it can be transported.

9. Marketing – During the focus groups, participants mentioned the need for better BCI marketing. Many participants had heard of the term, but had never seen a device or were unaware of the technologies capabilities. Participants indicated that BCI could be more socially acceptable if the right influencer promoted the devices. In general, BCI is currently marketed to a niche community and not the general public.

10. Price – The guidelines suggest that wearables should adopt the three-tier pricing model similar to smartphones and tablets. This pricing model would allow wearable technology to be accessible to a wide range of users. Currently, there are multiple tiers of BCI devices across companies. There are the medical grade devices that are priced in the $10,000 - $20,000 range. The lower tier medical grade used for research ranges from $500 to $1000. Finally the consumer-grade wearable devices can be purchased for fewer that $500. Some devices cost as little as $200. This is on par with other wearable devices on the market.

Some of the themes from this list came up in focus groups session and comments from users during user studies. This list has not be validated through empirical research but is a starting point to see how well BCI devices align with

wearable device suggested guidelines. As the prototypes in this research move to the next phases, these suggestions will be taken into consideration.

2.4 User-Centered Design

The UCD process is at the core of this research and influenced the design of the final hardware contributions. The International Organization for Standardization (ISO) standard 9241-210, on human-centered design (ISO, 2009), divides the process into four iterative phases as seen in Figure 2-11. It is an approach that supports the entire developmental of new products or services with user-centered activities (Holz et al., 2012). Its goal is to create products and systems which are easy to use and that are of added value to the targeted users (Holz et al., 2012; ISO, 2009). The UCD process emphasizes integrating the user early and often.

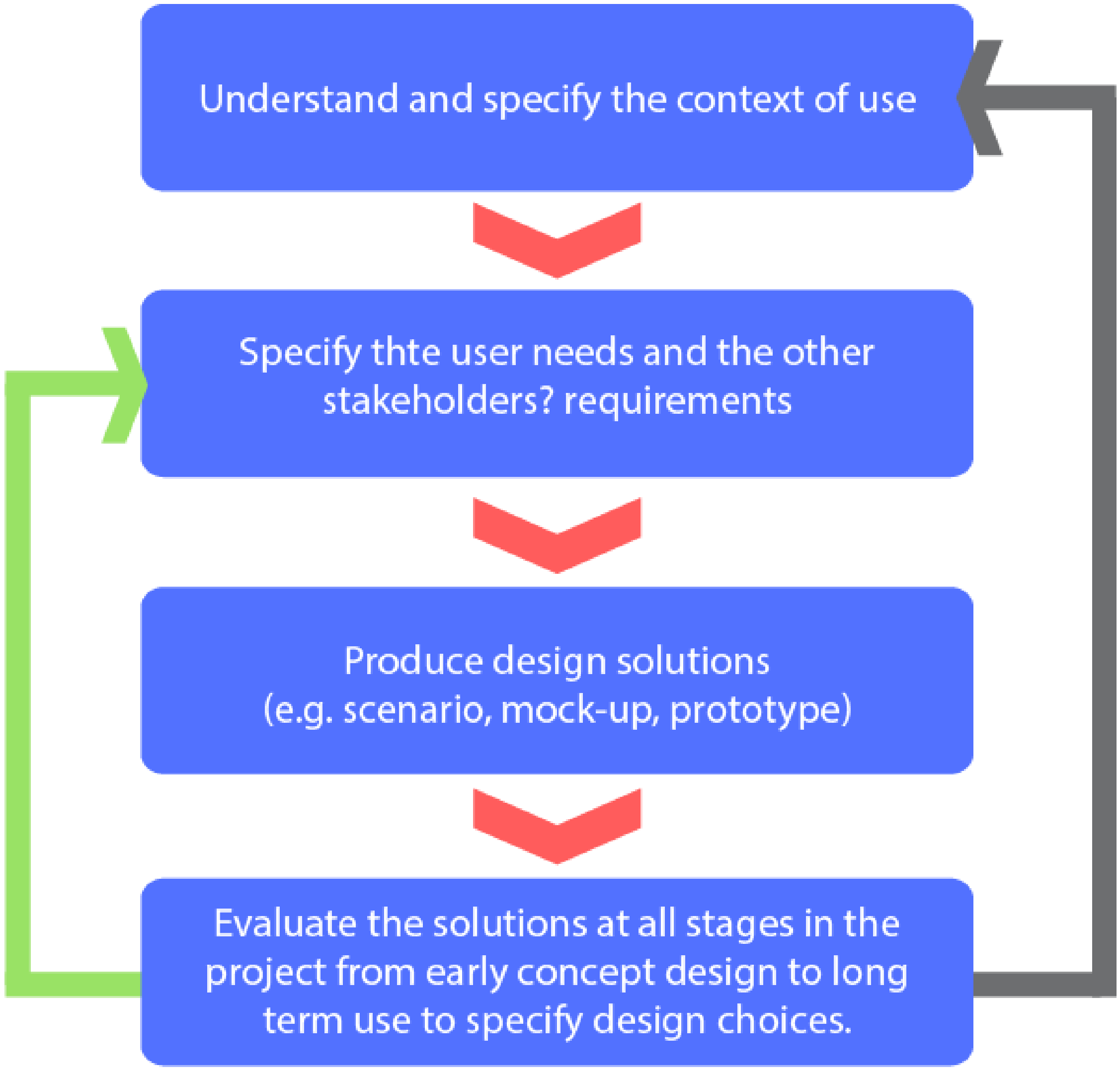

Figure 2-11. Phases of the user-centered design process

For this research the UCD process was applied to the development of three BCI device prototypes. Technologist often build technology first in hopes that people will adapt and find usage for it once it is created. Not designing with the user in mind from the beginning can waste money, time and resources (Nielsen, 1994). Because many wearable devices, including BCI, have come to market and commercially failed over the last few decades (Ryan, 2014), users were incorporated regularly throughout this

development process in an attempt to ensure user acceptance. Additionally, the current BCI field lacks much user-experience consideration.

The literature suggests that two factors negatively impacting user acceptance are the lack of usability and user experience consideration in the field (Lightbody et al., 2014). Most of the current evaluation methods focus on performance metrics with little usability or UX evaluation (Lightbody et al., 2014). The community suggests that more work needs to be done in this area to increase BCI usage and user acceptance (Bos et al., 2010; Bos et al., 2011).

A few BCI researchers have attempted to use this approach to evaluate or design BCI systems (Peters et al., 2015; Kübler et al., 2014; Holz et al., 2012; Kaufmann et al., 2013; Bai et al., 2010). Other studies (Huggins et al., 2015; Liberati et al., 2015; Blain-Moraes et al., 2012) have used select phases of the process and not the entire process. There are several factors that differentiate their work from this research. The researchers from (Peters et al., 2015; Kübler et al., 2014; Holz et al., 2012; Kaufmann et al., 2013; Bai et al., 2010) focused on non-healthy users, while this work did not. Evaluating and designing BCI devices for healthy users have a different set of user needs and constraints than focusing on non-healthy users. For example, healthy users are traditionally more mobile and therefore wired devices may be more problematic for them than it would be for a non-healthy user who is immobile. Also, BCI can be the only method of communication for some non-healthy users; therefore they may be less scrupulous about usability or aesthetics.

All of the previously mentioned studies evaluated or designed BCI systems using existing BCI devices for signal acquisition, while this research is focused on evaluating

only the signal acquisition hardware device and using the findings to design an improved device. A complete BCI system consists of the signal acquisition hardware device and the software used to process the data and provide user feedback. While much of the previous work focuses on the user experience of the software, it’s user interface and interaction, this work focuses on the experience with the hardware. This area is less explored. Although, some researchers (Ekandem et al., 2012; Mayaud et al., 2013; Duvinage et al., 2013; Hairston et al., 2014; Nijboer et al., 2015) have performed studies evaluating devices, more comparative studies need to be done with newer devices such as the Muse, Emotiv Insight and OpenBCI. The UCD process in this study involved the evaluation of three device prototypes and the comparative study of the OpenBCI device to determine barriers preventing women from using BCI.

CHAPTER 3
FEMALE DRIVEN USER-CENTERED DESIGN PROCESS OVERVIEW

3.1 Goals and Expected Contributions

In an attempt to address the issues of a lack of pervasiveness of BCI, this work took a female driven UCD approach to the development of a more fashionable, wearable BCI device. Women were the target group for this work because they face more difficulty using existing devices, even though they represent 66% of the target audience of all wearables created from 2014-2015 (Dunne, 2010). Skin contact is an important constraint when acquiring EEG signals through non-invasive BCI devices. Because women commonly have more hair than men, they face connection issues with many of the existing devices. These connection issues prohibit them from experiencing the benefits of BCI usage as well as participating in BCI related research studies. In addition to a lack of wearability, there is the lack of desirability. If women are to benefit from BCI as a wearable in addition to a research tool, they must be designed with specific considerations that include improving their ability to successfully wear the devices as well creating an aesthetic that would be acceptable for frequent wear. To investigate these issues, the following three main research questions were explored:

- (RQ1) What are the characteristics of a socially acceptable BCI device for women?
- (RQ2) In what ways does varying design decisions have an effect on usability when designing a BCI device for women?
- (RQ3) What are the effects, beyond usability, of varying design decisions when designing a BCI device for women?

This research offers several contributions to the BCI and wearable communities. This work has lead to the creation of three device prototypes that have been deemed socially acceptable. It provides a comparative analysis of the OpenBCI Ultracortex Mark IV EEG headset and devices designed for women. The OpenBCI headset had not been

evaluated in a comparative usability study prior to this work. A set of characteristics for socially acceptable BCI devices is also being presented to the community for future device development. As a result, a more comprehensive understanding of the barriers currently preventing women from using BCI more has also been achieved, as well as a breakdown of the tradeoffs between design decisions. Finally a more socially acceptable BCI device that allows women to perform cognitive tasks as well or better than an existing device was prototyped.

Target population: The target population consisted of college age women 18-30 years old. This group represents a solid portion of early adopters and is often the initial targets when new innovations hit the market (Pew and Hemel, 2004). It has been suggested that the college population can represent the general population well depending on the scale (Kelly and Gilbert, 2016; Spector, 1992). The creators of the WEAR scale, used in this research to evaluate the acceptability of wearables, actually sampled from a college population when they developed and tested the scale (Kelly and Gilbert, 2016). Finally, Johnson (2008) reported that college students were used in 19.1% of the published work on dress and human behavior; therefore it is appropriate to use this age group for this study.

Recruiting participants between the ages 18-30 is consistent with similar studies in the literature (Gürkök et al., 2011a; Mathe and Spyrou, 2015; Gürkök et al., 2011b). Additionally these research studies used between 13 and 20 participants. Traditionally BCI research studies do not have a large number of participants due to the significant amount of time it takes to run a single study. For this study 20 were used for the focus group and 30 participants were used for both usability studies.

3.2 User-Centered Design Approach

There are four main iterative phases to the UCD process (ISO, 2009). There are several different methods that can be utilized by UX researchers to complete each phase. Choosing the appropriate method is up to the discretion of the researcher and can be based on personal preference, desired data, as well as appropriateness for the task. Table 3-1 introduces the methods used in this research approach.

Table 3-1. User-centered design process and methods used.

UCD Process Phase	Method(s) Used During Phase
Understand & specify the context of use	Personal experience and observation in the field Literature Review
Specify the user needs & the other stakeholders requirements	Focus groups and interviews with the target user group User testing with target user group Review of existing wearable design guidelines
Produce design solutions	One pagers illustrating six proposed designs and physical props were shown to users in a focus group setting Based on feedback from design focus group, three device prototypes were created
Evaluate solutions at all states from early concept design to long term use to specific choices	Focus groups and interviews with the target user group were used to gather feedback during various stages of the iterative design process. User testing with the target user group was conducted once early on with an existing device to get benchmark data User testing was conducted to gather feedback once again when the prototypes were developed

The focus group method was chosen for several reasons; one being that it is an efficient tool for gathering data from multiple participants quickly. It is also a method of choice in highly exploratory research such as the early phases of this project. Because the focus of the focus group was on social acceptability and social messages, interaction among multiple participants and the social nature of focus groups substantiated the justification for selecting this method (Ulrich and Eppinger, 2008). Group conversation allowed participants to bounce ideas off of one another, which

proved to be useful. Interviews can be used when the researcher desires more detailed feedback from a user, and sometimes more honest feedback. Because the goal was to explore social acceptability, focus groups were the desired methodology as they create a social environment for the conversation. User interviews were used when the focus group was not an option, due to scheduling constraints. However, both methodologies resulted in very useful and rich information.

User testing was chosen to measure the usability of an existing device as well as the three prototypes. This method was used as a clear way to compare the existing devices with the new designs on key usability metrics as well as to get user feedback. A full explanation of the user testing experimental design and results can be found in Chapter 6.

Additional details about the methodologies used during each phase of the process will be elaborated on in further chapters, in context.

CHAPTER 4
WEARABLE BCI SOCIAL ACCEPTABILITY INVESTIGATION

The first phase of this work was highly exploratory and sought to investigate the characteristics of socially acceptable BCI devices. The goal was to produce a list of characteristics that can be used by BCI designers to create devices that are desirable to women. These guidelines also influenced design decisions for the three prototypes discussed in Chapter 5. Four focus groups of five people each were scheduled. Due to scheduling issues, there were three focus groups of five, one focus group of four and one individual user interview. The focus groups and user interviews were used to explore the answers to the first research question:

- (RQ1) What are the characteristics of a socially acceptable BCI device for women?

4.1 Experimental Design

4.1.1 Participants

20 female participants between the ages of 18-30 were openly recruited at the University of Florida. The study was advertised in the library, journalism school, computer science for non-majors class, as well as word of mouth through various social circles. The ethnic distribution was pretty even with 24% of the participants describing themselves as Asian or Asian American, 28% Black, 20% Hispanic or Latino and 28% Non-Hispanic white. The most common majors were in the College of Liberal Arts and Sciences and the College of Engineering with six and five people respectively. Other colleges represented included Agriculture and Life Science, Design, Construction and Planning, Art, Health and Human Performance, Education, Nursing, Law School, and one exploratory major. 75% percent of the participants reported owning a wearable, and the majority of them either only wear them 0-1 times a week or everyday. The key

wearable usages included: fitness, 44%, music/entertainment, 27%, mobile phone replacement/supplement, 16%, and as a basic clock, 11%. No on reported using their wearable for safety or non-fitness life-logging such as sleep monitoring or biometric data. Although, there were only 20 participants, these participants represented a wide range of majors, ethnicities and wearable usage patterns, by the end of the final focus group, it was clear that saturation had been reached.

4.1.2 Experimental Setup

The focus group took place at the University of Florida. Figure 4-1 illustrates the setup of the study room the experiment was held in. There were two tables in the room. Table one, not pictured, was used to electronically administer a pre-survey as well as attain written consent. The second table, pictured in Figure 4-1, was the main table for conversation. Several visual aids were used to drive the focus group conversation. Photos of models wearing existing BCI devices were placed on the table along with the respective device, as well as on display on the wall, this can be seen in Figures 4-2 and 4-3. Examples of existing EEG sensing headgear were displayed on the wall, as seen in Figure 4-3. A four-foot mood board, highlighting existing hair accessories women currently wear was also on display and is pictured in Figure 4-4. Details regarding the use of each visual aid will be discussed in the next section.

Figure 4-1. Focus group study room (Photo courtesy of the author)

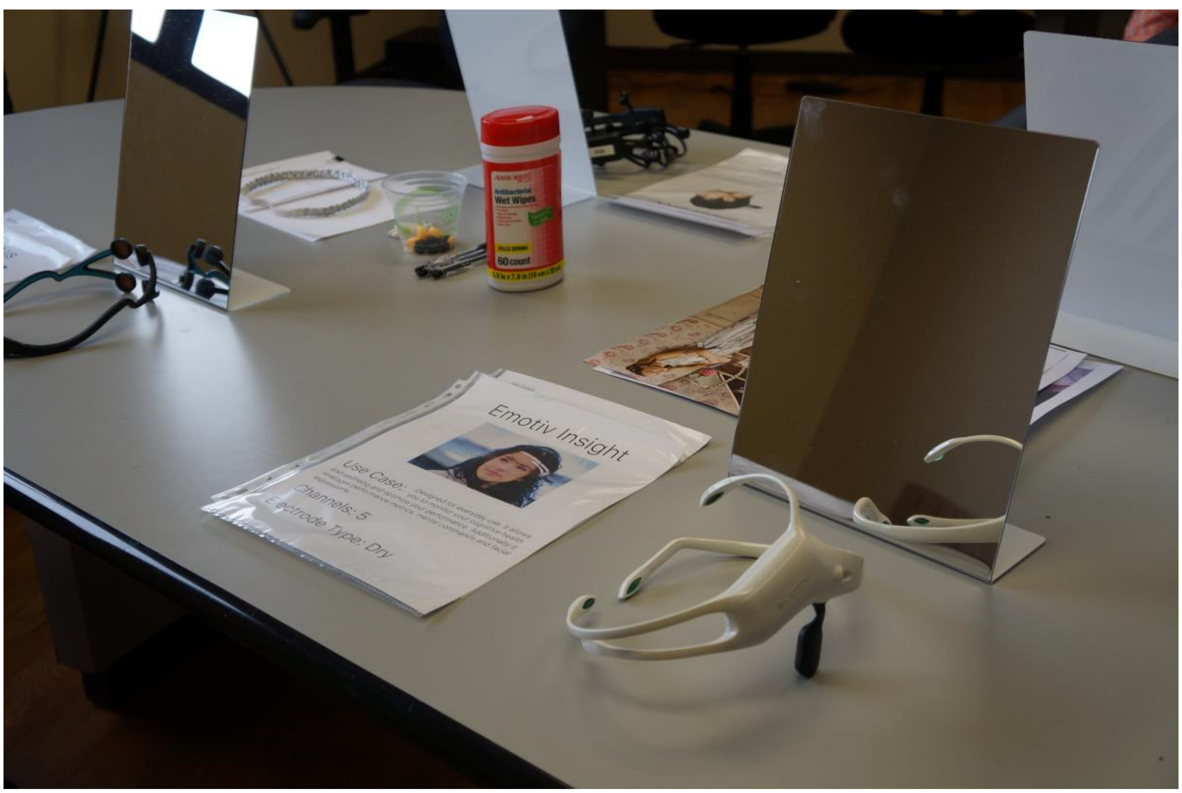

Figure 4-2. Emotiv Insight device and info sheet (Photo courtesy of the author)

Figure 4-3. Example EEG enabled headgear and BCI device info sheets (Photo courtesy of the author)

Figure 4-4. Moodboard with fashion hair accessories (Photo courtesy of the author)

4.1.3 Procedure

Upon entering the room, participants were seated at table one and asked to sign consent forms and to complete a Qualtrics pre-survey. The purpose of the pre-survey was to gather basic demographic data about participants, their existing knowledge of BCI and their current wearable usage. Following the survey participants transitioned to the second table where visual aids were used to drive the discussion.

Because the focus group was intended to be a semi-structured focus group, prompt questions and visual aids were used, however, the discussion was allowed to flow smoothly and openly. The major goals of the discussion were explained as well as an overview of the conversation topics to be covered. Next a high level overview of BCI as well as some sample use cases was explained. A printed copy of the list of use cases was also provided for each participant. The majority of the use cases focused on Affective BCI data, looking at user's emotional or cognitive state. Examples pertained to applications for work, home, gaming, education and Internet of Things (IoT) were also discussed. Additional motor-imagery examples such as using EEG to move prosthetic limbs were also used. Discussion prompts were administered, following the introductory information.

Participants were first asked if they had heard of BCI and what they currently use it for. Next they were asked to discuss what they could see themselves using it to do, based on what they had learned about the technology. They were then informed that they could try on each of the devices and pass them around. Feedback on existing devices was then requested questions like "How do you think you look", "Would you wear this in public", and "What social messages does this send about the person wearing it " were posed. Additional questions around social messages were discussed

and participants were asked to rank the existing devices in order of preference on a half-sheet of paper provided. Current wearable usage was discussed including; devices currently owned, frequency of use, and deciding factors when choosing to wear a specific device. Participants were asked to discussed existing wearables they considered to be socially acceptable and what they liked about them. Next, they were asked about the level of social acceptability of the BCI devices they tried on. Additionally, they were asked for suggestions in making BCI more desirable and socially acceptable.

The last section of focus group was centered on existing headgear and accessories. Participant's attention was directed to the mood board in Figure 4-4 and the headgear on shown in Figure 4-3. They were asked about their current usage of headgear and head worn accessories, such as hats, headbands, combs, helmets, etc. They were also asked about their interest in wearable headgear or accessories with embedded EEG sensors. During this final portion of the discussion more details were given about the Narbis, Smart Cap, Mindrider, and Kokoon devices. Finally the floor was open for additional comments, feedback or general suggestions. Following the discussion each participant was thanked for their participation and given a $15 visa gift card. The audio/visual recordings from each session was transcribed and coded using the Atlas.ti software.

4.2 Data Analysis

Over 500 codes were created using various coding schemes. During second cycle coding, new codes were added, while some existing codes were reimagined. Following the second cycle, the codes were organized into 25 code groups based on emerging themes. One of the coding groups represented characteristics of socially

acceptable BCI devices. This group was further evaluated as the basis for the list of recommended characteristics that will be presented in this work.

4.2.1 Coding Process and Schemes

The Coding Manual for Qualitative Researchers was used as a guide when determining the best coding schemes for this work (Saldaña, 2015). Originally the transcripts were printed and the first cycle coding was done by hand. The overall coding strategy for this research was of an evaluation nature. Participants' evaluation and feedback of the existing devices was the basis for much of the focus group discussion. An open coding scheme, that Johnny Saldaña calls Eclectic Coding, was employed for the transcript data (Saldaña, 2015). Eclectic Coding involves using a combination of two or more strategically chosen coding methods to annotate a data set. The following codes were used to contribute to the Eclectic Coding scheme:

- Attribute Coding was used to help organize and identify key information. For example, the participant speaking and the specific device being discussed were coded by participant number and device name.
- Magnitude Coding was used in conjunction with attribute coding to specify participants' sentiment towards each device. For example, the code *Insight (+)* was used to represent positive statements toward the Insight device.
- Subcoding was used in an attempt to be slightly more descriptive with codes that were common but vague. For example, the *appearance* code was used 45 times. However, appearance alone did not fully capture what the participant was saying. A subcoded example such as *appearance.weird* indicates that the participant was talking about appearance and described it as weird.
- Simultaneous Coding was used when necessary. For example, a statement may be coded with the attribute magnitude code to represent the device and the sentiment, while an additional appearance code would describe the actual feedback.
- Structural Coding was used to label or index the participants' responses. Many of the structural codes were subcoded. For example, the structural code, *social messages* was subcoded with gamer to be *social message.gamer* when a participant indicated that the device's wearer looked like a gamer. Additionally,

the structural coding in some cases related directly to the research question, such as responses to an inquiry about characteristics of a socially acceptable BCI device.

- Descriptive Coding was used to denote content topics. *Color*, *comfort* and *appearance* were all used as descriptive codes. For analysis and organization purposes statements were coded with the descriptive code as in and then later subcoded. Therefore a statement would be coded *color* and *color.white.*

- In Vivo Coding was not used explicitly, however user statements were recorded and used as subcodes for some structural codes such as *suggestions* or *social message.dweeb*. Dweeb was a term used by the users in a focus group.

- Provisional Coding is used when there are anticipated response categories and a predetermined start list of codes can be established. Although most of the codes used developed organically from the data there were a few anticipated categories such as the *socially acceptable characteristics* code or the *social message* code. It was known in advance that responses to certain prompts by the researcher during the focus groups would result in responses that would fall in those categories.

After the data was coded by hand, the transcripts were recoded electronically. During this second cycle, many of the written codes were copied into Atlas.ti. Because the full data set had been coded by this point, a more complete picture of the data could be drawn. It became apparent that there was some overlap in the code-naming. Codes with similar meaning were evaluated and combined or rephrased where appropriate.

Atlas.ti was used to organize the codes into 25 code groups or thematic categories. The categories can be seen in Table 4-1. Some of the categories such as Participant Codes or Positive and Non-Positive codes were created for organizational and analytic purposes, and were not expected to translate into a theme or characteristic. Other categories such as the two dedicated to socially acceptable characteristics contributed directly to the list proposed to the wearable BCI community. During the focus group, participants were asked to indicate what characteristics they thought should be attributed to a socially acceptable BCI device. The responses to that

question were characterized in the group marked “explicit”. After some consideration, it was decided that other codes from the data could also represent characteristics and were therefore included in the code group labeled “implied”. This code list was the basis for the analysis that would address the research question.

Table 4-1. Focus group code categories

Code Group Names	Example Code
Appearance Attributes	appearance.headband
Characteristics of Socially Acceptable BCI Devices (Implied)	willing to wear
Characteristics of Socially Acceptable BCI Devices (Explicit)	social acceptability.trendy
Colors	color.white
Comfort	Comfort.discomfort
Device Affinity	Muse(+)
Ease of Use	ease of use.unwilling to wet
Hair	hair.style dependent
Hairstyle	hair.style.pony tail
Headgear	headgear.hats
Lack of Awareness/Knowledge	need a use for BCI
Misleading Appearance	not as bulky as they appear
Non-Positive Codes	social message.dweeb
Participant Codes	P1
Personal Style	personal style.girly
Positive Codes	appearance.cool
Social Acceptability	social acceptability.location
Device’s Social Messages	social message.illness
Socially Acceptable Wearables	socially acceptable wearables.Fitbit
Suggestions for Future Devices	suggestion.fashionable foreheadband
Use Cases	use case.education
User Preferred Social Messages	social message.pref.put together
Versatility	suggestion.variety
Wearable Choice	wearable choice.price
Wearable Usage	wearable usage.outfit centric

4.2.2 Analysis Process

The Atlas.ti software was used to analyze the data. Tools such as co-occurrence tables were used to investigate patterns and codes that may have been related. Code groups were placed in co-occurrence tables with the Participant Code group so see the

frequencies at which participants mentioned popular codes. It was suggested by Namey et al. (2008), to look at the number of participants who mention a theme not just the number of times the theme appeared. This was taken into consideration and both methods were seen as valuable when trying to understand the dataset. However, the number of times a theme occurred was used during the beginning stages of analysis for the characteristics list. Atlas.ti uses the term “groundedness” to refer to number of occurrences.

The list of suggested characteristics for socially acceptable BCI devices was derived from the analysis of the code group labeled “implied”. Because there were 98 codes on the implied list of characteristics many of which only had a groundedness of 1, the decision was made to clean the data. Codes with a groundedness of 1 were either merged or removed. Codes that were not originally coded as characteristics and were redundant were removed from the code group. Redundant codes were merged. For example, Socially Acceptable Charateristic.subtle was merged into Socially Acceptable Charateristic.invisible. After several items were merged, 68 codes remained.

An Excel sheet was created to begin organizing codes as they formed into an understandable list of characteristics. The 68 codes were translated into actual sentences that represented characteristics/suggestions. In some instances, more than one code was combined to support the rationale for a characteristic. A chart with each characteristic and all the codes that supported the characteristic was created. The groundedness from each of the support codes was compiled to represent the groundlessness for the characteristic it supported. For example, the code Socially Acceptable Characteristic.customizable was translated to the statement, “The device is

customizable allowing for versatility". A total of 14 codes were used to "support" that characteristic. A sample from the chart can be seen in Table 4-2. The first column shows the characteristic "The device is customizable allowing for versatility", the second column is a comment or brief description, the third column has all the support codes and the fourth column shows the groundedness.

Table 4-2. Example Characteristic and Support Codes

Characteristic	Comment	Support Codes	Groundedness
The device is customizable allowing for versatility	Users reported a desire to be able to customize the device to make it more suitable for various outfits, hairstyles, and destinations as well as to match their style	social acceptability.trendy	18
		wearable choice.trend	3
		personal style.trendy	2
		need to increase user's understanding of BCI's capabilities	4
		need more advertisement	3
		social message.create curiosity	10
		suggestion.influencer	1
		wearable choice.peer influence	6
		wearable choice.family influence	5
		wearable choice.brand recognition	5
		wearable choice.social interaction or inclusion	2
		wearable choice.lack of knowledge	2
		wearable choice.advice from techie friends	1
		wearable choice.advertising	1

After all of the characteristics were organized into this chart, another chart was created that indicated the groundedness for each characteristic based on the support codes, but across all participants. This chart indicated the number of times each of the 20 focus group/user interview participants' statements were coded with each support code. The co-occurrence tool in Atlas.ti was used to generate the data for this chart. A

co-occurrence function was run to compare participants' responses with each support code. This chart was used to calculate a Cronbach's Alpha coefficient.

Cronbach's Alpha is a coefficient of reliability and measures internal consistency. It indicates how related a set of items are. Most social science research considers a value of 0.70 or higher to be acceptable. The coefficient was used to determine the interconnectedness among the suggested list of 32 characteristics. The resulting coefficient was a 0.855, this confirmed that the characteristics are highly interconnected and are a good set of descriptors for BCI social acceptability for women. The Cronbach's Alpha value is often used in the creation of standardized scales when researchers are testing if the questions are proper measures of the subject matter.

The future of this work is to continue to test and refine the characteristic list, determine if it is appropriate to make a standardized scale from the characteristics, and to see how the list can be applied to other head worn wearables. The full list of characteristics can be seen in Table 4-3.

Table 4-3. Characteristics of socially acceptable BCI devices

#	Characteristic
1	Social acceptability can be influenced by the wearers personal appearance
2	Users must be willing to wear it
3	Devices can contribute or at minimum do not detract from it's users' outfits
4	The device uses dry electrodes
5	The device is easy to put on
6	The device blends in well
7	The device is customizable allowing for versatility
8	The device is popularized
9	The device is not bulky
10	The device is compatible with various hairstyles
11	The device is affordable
12	There is a need for the device
13	The device is appropriate for various social settings
14	The device has a sleek design
15	The device has unique features and is high quality
16	The device is easy to maintain
17	The device is not painful and does not leave visible marks on the wearer
18	The device is comfortable to wear
19	The device resembles existing accessories
20	The device looks "cool"
21	The device is light weight
22	The device is suitable for use with earrings
23	The device is adjustable and fits various head shapes and sizes
24	The device is easy to use
25	The device is stylish and fashionable
26	The device solicits positive attention
27	People wearing the device, do not appear to be trying too hard
28	The device has good battery life and does not drastically drain the other devices it is connected to
29	The device helps and does not hinder social interaction
30	The device has a minimalistic design
31	The device is offered in a variety of staple color options
32	The device is visually appealing and has a positive social message

4.2.3.1 Wearable Design Guidelines Revisited

Chapter 2 describes an aggregated list of wearable design guidelines. The list was categorized into 10 major themes. The above list found in Table 4-3 was mapped to the 10 wearable guidelines. Many of the characteristics for socially acceptable BCI were easily sorted into one of the major themes. There were seven characteristics that did not inherently fit. These characteristics can be seen below in Table 4-4.

Table 4-4. Abbreviated characteristics of socially acceptable BCI devices

#	Characteristic
1	Social acceptability can be influenced by the wearers personal appearance
10	The device is compatible with various hairstyles
16	The device is easy to maintain
22	The device is suitable for use with earrings
26	The device solicits positive attention
27	People wearing the device, do not appear to be trying too hard
29	The device helps and does not hinder social interaction

4.2.3 Additional Insights

In addition to the development of the socially acceptable characteristics the focus group uncovered additional insights. Throughout the focus groups, headphones were mentioned 117 times. Many users used the word headphones to describe the devices. The term referred to telecommunication headphones that have a microphone protruding as well as traditional headphones. This is interesting because all the participants agreed that headphones are socially acceptable and although they compared some of the devices to headphones, the general sentiment was that the existing devices were not socially acceptable.

During the focus groups users gave feedback on existing devices. They were asked to express the social messages they felt the devices communicated to other people. They were also asked to share the social message they themselves like to send. Additionally, they were asked to describe their personal style. The most common response was that their social message was location dependent. For example, many users reported that their message is different when they are on campus or going to class versus when they are going downtown or “out”. One user stated that her clothing communicates what she has to do for the day. If she has to work, she will be wearing her work uniform, if she is going to class, she wears a certain set of clothing, and if she

is going to the gym, she wears workout attire. Her preferred social message was coded as “agenda”, because her attire communicates her agenda for the day. There were 53 codes that initially represented participant’s preferred social message and personal style. Of the 24 codes used to describe the social message of the existing devices, only five aligned with the preferred messages and style. The most common social message used to describe the device was gamer. None of the participants reported having the desire to send that message. In fact, the majority of the participants who used the term, meant for it to have a negative connotation.

By examining the co-occurrence table comparing social acceptability codes and subcodes with the devices, it is clear that participants thought the Focus device appeared to be something from a science-fiction movie. Several participants even referred to the device’s appearance as “Looking like alien fingers”. The Neurosky was coded as weird several times. While the Insight was seen as something that is not currently acceptable, but once more people start to wear the device, “it could be cool”. Some participants said it looked like an Apple product. Marketing and a need for exposure was a trend throughout the focus groups. Participants explained that if the right influencer or celebrity wore the Muse or the Insight, they would become more acceptable. Particularly the Muse, it was the device people were most likely to wear.

The codes were filtered for non-positive comments and positive comments. There were more non-positive comments than positive comments. There were a total of 51 positive codes used a total of 196 times. While there were a total of 80 non-positive codes used a total of 427 times. The Muse device was the most popular device, it was mentioned 134 times and received the most positive feedback. The Insight, Focus,

EPOC, and Neurosky were mentioned 78, 77, 59, and 45 times respectively. Based on the co-occurrence table, the Insight was viewed as the most uncomfortable device with 14 co-occurrences between the discomfort and Insight codes.

The ease of use code was used over 40 times. Every user reported some type of difficulty with the devices' ease of use. The major ease of use complaints referenced difficulty using the devices and being unwilling to wet the sensors continuously throughout the day. For example, many users had difficulty mounting the devices either due to interference with their hair or not understanding how the device should be placed on their head. Each device came with an accompanying picture of a female wearing the respective device, but some users still reported difficulty getting the devices on. Two of the devices in the focus group required wet electrodes, The Emotiv EPOC and the Focus. There was a significant amount of push back from the idea of wearing a device that required wet electrodes. Although participants were not asked to place the wet electrodes on their head, there were saturated electrodes on the table during the focus group as examples. Only one user reported being willing to wet sensors on the Focus device. It was later discovered that she does not wear make up so the wet forehead sensors would not present a problem for her. Because participants felt so strongly about their refusal to wet sensor, the use of dry sensors was added to the list of characteristics.

Other top complaints were a result of the devices not fitting well on users' heads or the Neurosky's ear clip interfering with their earrings. This turned out to be a latent need because it was later discovered that all of the participants wear earrings everyday. Some users even reported being willing to turn around and go back home if they forgot

their earrings. This had implications on future design suggestions. Any design recommendation must account for the fact that many women wear alteast one pair of earrings regularly. Some participants even suggested to include earrings in the device design, since it is an accessory that woman are accustomed to wearing anyway.

Post-bias check: A second researcher coded approximately 10% of the data, using the code book provided by the primary researcher. The inter-rater reliability was around 50% for this sample subset of the data. This number may have resulted due to the fact that researcher 2 did not use as many codes as researcher 1. There was much agreement among the codes that were used, however because researcher 1 used several codes that researcher 2 did not, the reliability appears to be low. It is believed that if a second round of coding was done with the full data set and a moderator, this number may be higher.

4.2.4 Summary

This chapter presented the findings from the initial user focus group. Qualitative research methods were used to analyze the focus group findings. The result was a list of 32 characteristics for socially acceptable BCI devices for women. Future work is to continue to distill the list and explore additional applications such as standardized guidelines for other head worn wearables or a standardized questionnaire for socially acceptable BCI devices. Subsequent analysis could explore assigning a ranking system to indicate the importance or impact of each characteristic. They are currently ordered by decreasing groundedness. In additional to the list of characteristics, several latent needs were uncovered. All of the findings were used to influence the design of three BCI prototypes.

CHAPTER 5
FASHIONABLE BCI

Sabrine Seymour describes fashionable technology as considering "end users as fashionable beings, attentive to style, aesthetics, branding, and the expressive potential of wearable technologies" (Seymour and Beloff, 2008). Wearable technology or wearables are defined as electronics or computers that are integrated into clothing and accessories that can be worn comfortably on the body (Michael, 2014). BCI devices are head worn devices that are capable of sensing user's EEG data. The UCD process is a UX tool utilized in the product development cycle. When all of these fields merge, as in Figure 5-1. the result is Fashionable BCI.

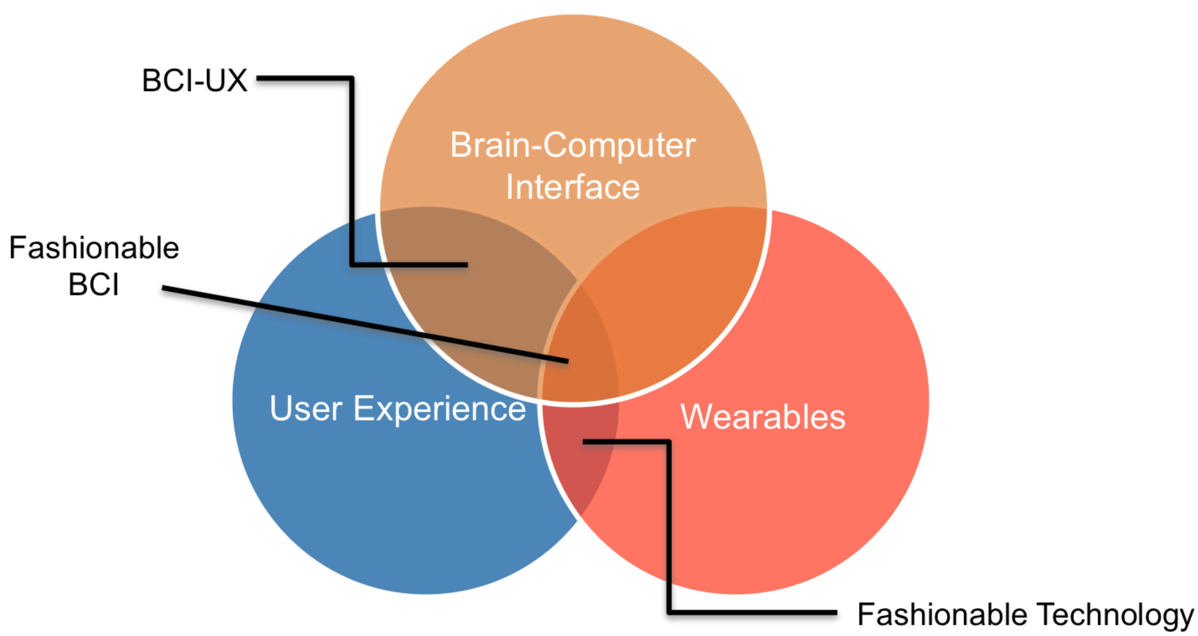

Figure 5-1. Fashionable BCI is the intersection of BCI, UX, and Fashionable Technology.

One of the goals of this work was to get a better understanding, through user research, of how BCI devices can be designed more fashionably. The premise was that by improving the aesthetic and making a device fashionable, would improve the social acceptability (Norman, 2005; Tractinsky et al., 2000). The first focus group was used to

gather feedback on existing devices, better understand wearable usage decision making, and receive suggestions for future socially acceptable devices. Following that focus group, qualitative research methods and practices were used to establish a list of 32 characteristics of socially acceptable BCI devices. This list as well as general qualitative feedback was used to come up with six design suggestions.

5.1 Design Solutions

Following the focus group and qualitative data analysis, it became clear that the best design ideas would leverage existing headgear. Women currently wear so many accessories on their heads from hats and headbands to bobby pins. The focus group participants were particularly interested in enabling existing headgear as opposed to a brand new BCI device. Participants were interested in wearables that could be customized based on their personal style and where they were going, outfit centric wearables that did not detract from their outfit or hairstyle, and items that looked like accessories as opposed to technology. The six one-pagers seen in Figure 5-2 – Figure 5-7 were created to represent each design idea. Each one-pager was labeled A-F and contained images of existing headwear or accessories, a succinct description of the idea, and design considerations to be decided.

5.1.1 One-Pagers

The traditional headband design was intended to represent the common headband style worn on the top of a head. Comb like sensors were suggested to penetrate various hair textures and density. This design addressed the desire to have a device that is socially acceptable by taking on the form factor of a regular headband. Additionally, the comb like sensors addressed the need to work well with various hair

types. The main consideration left for discussion was user preference for a fabric, elastic, or rigid headband.

Figure 5-2. Traditional headband one-pager

The forehead headband was inspired by the Muse and Melon design. The Muse device had the most positive feedback in the focus group of the existing devices. However, participants did express a desire for the device to be “cuter” or more fashionable. Some participants even expressed that the portion that rests behind the ears was too bulky. The forehead band design idea represents a device that looks more like a hair accessory than a piece of technology. Because this headband would rest on the scalp, there would be no interference with the wearer’s hair or hairstyle. A

discussion around the material and level of embellishment was left for a future focus group with users.

Figure 5-3. Forehead headband one-pager

The dual-wear headband was a design that would allow for users to switch between the traditional top of the head location and the forehead location. This was for elastic or soft headbands that could be comfortably worn in both positions. This would allow for the fabrication of one device that could be worn by people with a preference for either design. One of the major drawbacks of this proposed design was the need to change the sensors. It would be the wearer's responsibility to switch out comb sensors with flat sensors, when changing modalities.

Figure 5-4. Dual-wear headband one-pager

Because contact with the scalp is so important the barrette/brooch design was suggestion. These hair accessories clamp the hair tightly and by default naturally have the best contact with the scalp. This one-pager presented the various clipping accessories currently used. The idea was to have a comb sensor on the bottom portion of the clip, a thin casing to house the board, battery, and wires, and decorative face on top.

Figure 5-5. Barrette/brooch one-pager

Some participants expressed a desire to not want to wear the same thing everyday. The fifth design idea, the transferable sensor plate would allow users to enable their existing headgear. This design would allow users to take hats or headbands they already own and make them a BCI device. The transferable sensor plate would be small and concealable under other headgear. The plate was intended to utilize flat forehead sensors.

Figure 5-6. Transferable sensor plate one-pager

The final design idea was the interchangeable face plate. Customization was one of the top needs uncovered from the focus group. This design addressed customization and socially acceptability. Users would be able to switch the face plates on the headband similarly to how they currently switch the faces on their smart watch and other wearables. Discussions around whether this design should be a forehead headband or a traditional headband were saved for a future focus group with users.

Figure 5-7. Traditional headband one-pager

These one-pagers were used in a second design iteration focus group to gather user feedback.

5.2 Design Iteration Focus Group

The purpose of the design focus group was to get user feedback on the six design ideas and make a decision on which ideas would be prototyped, removed or combined with another idea.

5.2.1 Participants

Because this focus group was intended to get quick feedback as a part of the iteration process, only 10 participants were used. The same target age range of 18-30 was recruited.

5.2.2 Experimental Design

The design focus group took place in the same room at the University of Florida as the first focus group. During this focus group, only one table was utilized. Figure 5-8 shows the room set up and the visual aids used to drive the conversation. In addition to the one-pagers, various headbands and hair accessories were also used as visual aids.

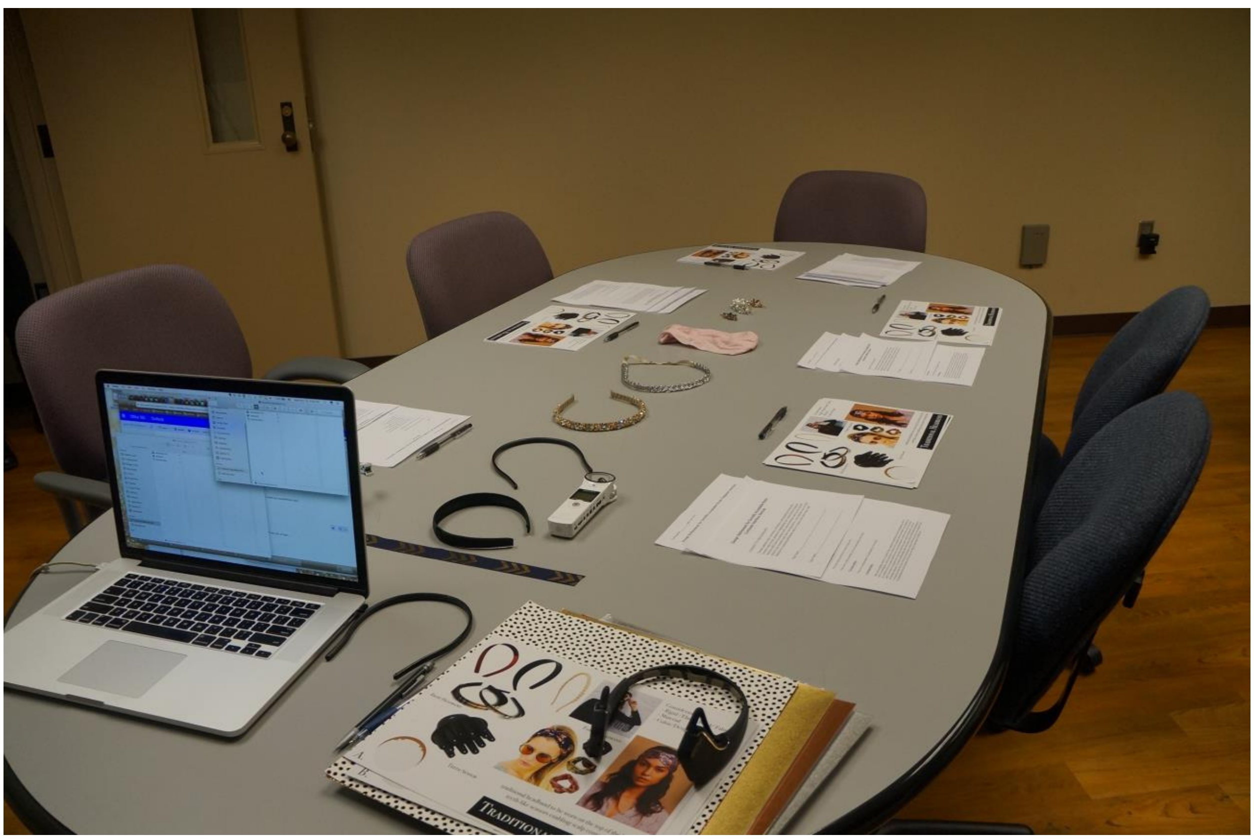

Figure 5-8. Iterative design focus group (Photo courtesy of the author)

The visual aids were used in addition to a few prompts to drive the semi-structured discussion. The discussion asked users about their general feedback and

preferences in regards to the six design ideas. Questions about specific aspects or features of each design that were favorable or disliked were also asked. Additionally, participant's willingness to wear and social acceptability were discussed.

Following the conversation, participants were asked to rank their preferences from the design ideas. They were asked to write down the name of the designs they liked or a combination of multiple designs that can form one design idea moving forward, on a preference sheet provided. The results from the focus group indicated that users liked the rigid traditional headband as long as it was flexible and not painful. They also liked the transferable sensor plate and an elastic forehead headband with interchangeable faces. The idea of the forehead headband being out of their hair was favorable even though many people reported not currently wearing that style of headband often. Based on the feedback from the design focus group, the rigid traditional headband, an elastic forehead headband version of the transferable sensor plate, and an elastic headband version of the interchangeable face plate were chosen to move forward into the prototyping and final test phase.

5.3 Fashionable BCI Prototypes

Three prototypes were conceptualized using feedback from both focus groups and with the 32 characteristics of socially acceptable BCI devices in mind. All three prototypes were built using OpenBCI technology and EEG sensors from Florida Research Instrument. This section will offer more details about the prototypes and how they were constructed.

5.3.1 Traditional Headband

During the focus groups, a new flexible rigid headband from Scuncii was used as a visual aid for the rigid headband design. Users liked the idea of a traditional headband

but did not initially respond well to it because of bad experiences. Users reported experiencing discomfort and pain over time with traditional rigid headband. When they discovered that a truly flexible headband had been created, this design was highly favorable. Participants responded overwhelmingly to the flexible design and made it a requirement for the rigid headband prototype. Therefore the wider version of the headband used in the focus group was purchased to construct the prototype. The prototype is pictured in Figure 5-8.

The primary issue with this headband was getting the sensors to adhere to the rubber on the underside of the headband. Several adhesives were tested for the prototype including, hot glue, E6000, Loctite Super Glue and Gorilla Glue. The hot glue peeled off immediately. The Loctite Super Glue proved to be the best adhesive after curing for the full two days. In order to construct the prototype, the measurements for the sensor placement were marked on the headband, the wires were painted black with acrylic paint and the sensors and wires were glued to the headband. The same medium OpenBCI headset used in the first usability study was used as a measurement guide when marking the electrode placements on the prototype headbands.

The actual device is intended to have four sensors placed at F3, F4, Fc5, and Fc6, with reference and ground electrodes located at Tp9 and Tp10 in accordance with the 10-20 system (American Electroencephalographic Society, 1994).
However, only two active sensors, F3 and F4 were used for the drone simulation task in the usability study discussed in Chapter 6. Ear clips serve as the ground and reference for the OpenBCI board used to prototype the devices. The benchmark study utilized the two forehead sensors (Fp1 and Fp2), so to be consistent, only two sensors were

actively used for all three prototypes in the final usability study. All of the sensors used for the prototypes and benchmark test were frontal lobe sensors and can be used to gather the same type of data. In the case of this study, engagement was measured using, alpha, beta and theta waves. The sensor placement was also based on where females wear traditional headbands on their head, in relation to the 10-20 system. Because the headband is flexible, the sensors were not in the exact same place on every head size and shape. However, this is no different from how current adjustable headsets fall in slightly different places on various heads, but spatially speaking the sensors are in a close enough proximity of the intended location to gather the necessary data.

Figure 5-9. Traditional headband prototype (device a) (Photo courtesy of the author)

5.3.2 Transferable Sensor Plate

This prototype is intended to be a thin and concealable forehead headband. It was decided to use an elastic headband and foam backing to hold the sensors in place. Flat sensors from Florida Research Instrument were used to collect EEG data from the forehead location. The foam backing can be seen in Figure 5-9. Several elastic headbands were tested before one was chosen for the prototype. A moderately thick medium width headband was chosen for comfort, durability, and stretchiness. A 3/8" diameter foam roller was sliced in half for the foam sensor housing. The openings for the sensors were measured and cut. Finally, the wires were connected to the sensors and the foam was glued to the elastic headband. The prototype can be seen in Figure 5-10.

This headband as well as the third prototype took inspiration from the Muse device, which utilizes four sensors and a reference. Using the OpenBCI system, the active sensors were placed at Fp1 and Fp2. The additional sensors, would be placed at F7 and F8, with ground and reference sensors located at Tp9 and Tp10. Again, only two sensors were used for the simulation exercise.

Figure 5-10. Foam sensor housing for transferable sensor plate prototype (device B)
(Photo courtesy of the author)

Figure 5-11. Transferable sensor plate prototype (device B) (Photo courtesy of the author)

5.3.3 Interchangeable Face Plate

An existing elastic headband was used for this prototype. This headband was decorative with black beading. During both focus groups, many participants expressed a desire for black or other neutral base colors. The same flat sensors from the previous prototyped were used, however, instead of a foam sensor housing, a short piece of black elastic was used to secure the sensors and conceal portions of the wire. The same sensor placement was used for both forehead headbands.

Figure 5-12. Interchangeable faceplate prototype (device c) (Photo courtesy of the author)

5.2 Chapter Summary

This chapter explained how qualitative research was used to influence the design and conceptualization of three BCI prototypes. Feedback from the initial focus group and the list of socially acceptable characters were used to inform the creation of six design ideas based on existing headgear. Those six ideas were placed in front of users during another focus group to gather feedback and preference information. All of that data informed the design and creation of three headband prototypes that can be further refined, improved, and productized. In addition to the qualitative data, two usability studies were performed with the goal of getting any accompanying quantitative data. One study was performed as a benchmark task before the design focus group and the final study was performed at the conclusion of prototype development.

CHAPTER 6
USABILITY STUDIES

A female-driven UCD process was used to design three alternative device prototypes. Two usability studies were performed to compare the prototypes to each other and a benchmark device. The qualitative and quantitative data was analyzed to investigate the trade-offs BCI designers must consider when building devices for women. The usability testing was used to answer the following research questions:

- (RQ2) In what ways does varying design decisions have an effect on usability when designing a BCI device for women?
- (RQ3) What are the effects, beyond usability, of varying design decisions when designing a BCI device for women?

Usability measures effectiveness, efficiency, and satisfaction (ISO, 1998). The user studies will measure those three components in the context of BCI usage.

A performance task was used to measure effectiveness. Users were asked to complete three brain-drone flights with the drone simulator previously used for the brain-drone race. In the simulation environment users were tasked with using a single command (forward) to move the simulated drone pass the finish line. The simulator interface can be seen in Figure 6-1. An average of the task completion times for three attempts was taken as a measure of performance. In order to incentivize participants to perform with effort, the top performer at the conclusion of the user studies was awarded an additional $25 gift card.

Figure 6-1. Brain-Drone Race simulator

The mounting experience was used to measure efficiency. Subjective user feedback about the mounting process and its ease of use was gathered. Likert scale questions allowed participants to self-report their perceived ease of use (with regard to mounting). Additionally, participants were given the opportunity to elaborate on the mounting experience and ease of use during the post interview process.

Post surveys were used to measure user satisfaction. The Comfort Rating Scale (CRS) (Knight and Baber, 2005) and the Wearable Acceptability Rating (WEAR) Scale (Kelly and Gilbert, 2016) were used in addition to custom BCI specific questions.

The usability of an existing device, the OpenBCI Mark IV Ultra Cortex Headset, was compared to the usability of the three new prototypes. The first study was used to determine baseline benchmarks and target specifications for the new devices being

designed. Prior to the second study, insights from the focus groups, first usability study, and the second design focus group were used to design and prototype three new devices. The second study was a within-subject comparative studying evaluating the three prototypes, and will be discussed in detail later in this chapter.

6.1 BCI Pipeline – Connecting OpenBCI, OpenVibe, and the Web

Task completion time is a common metric used for BCI tasks. For this study, the simulation used for the Brain-Drone Race was chosen as the task, because it was easy and fun. Additionally, the system supported additional extensions. This project contributed additional components that were not previously supported, therefore a custom signal/command pipeline was created. The same pipeline was used for both usability studies. This section will give an overview of the hardware and software components of the pipeline.

6.1.1 Hardware

OpenBCI was used as the signal acquisition device in the BCI pipeline. The Cyton board from OpenBCI, seen in Figure 6-2, is an 8-channel biosensing amplifier that can measure electrocardiography (ECG), electromyography (EMG), and EEG. It connects to the computer wirelessly via USB and samples data at rate of 250Hz. The OpenBCI company sells the Ultracortex “Mark IV” EEG Headset in Figure 6-3 on their website. It is a 3D printed headset that can be used to place up to 16 sensors. However, the board can be used with any form factor. Because this technology allows researchers to build highly customizable EEG devices, it was deemed appropriate for this study. In an effort to be consistent across both usability studies, the same Cyton board and signal/command pipeline was used. Because the Mark IV headset is the base model that is offered by the company, with no modifications, it was used as a baseline in the

first usability study. The second usability study used prototyped form factors with the same board.

All of the EEG sensors and electrical components used were from Florida Research Instrument. This company provided the components OpenBCI used to assemble to Mark IV and their components were also used to assemble the three prototypes. Florida research instrument offered special equipment for the OpenBCI board. The two forehead headbands used flat EEG sensors similar the ones found on the front of the Mark IV headset. However, the traditional headband, used the comb-like sensor seen in Figure 6-4. This sensor was used to help better penetrate users' hair. Unlike the lead wire shown in Figure 6-5, the wires used in this study did not have safety jacks, instead they had the connections for the OpenBCI board seen in Figure 6-6. Because OpenBCI uses ear clips for the ground and reference signals, all four devices, including the prototypes had two ear clips. In order to enable the OpenBCI board to communicate with the Brain-Drone Race simulator, custom software was created.

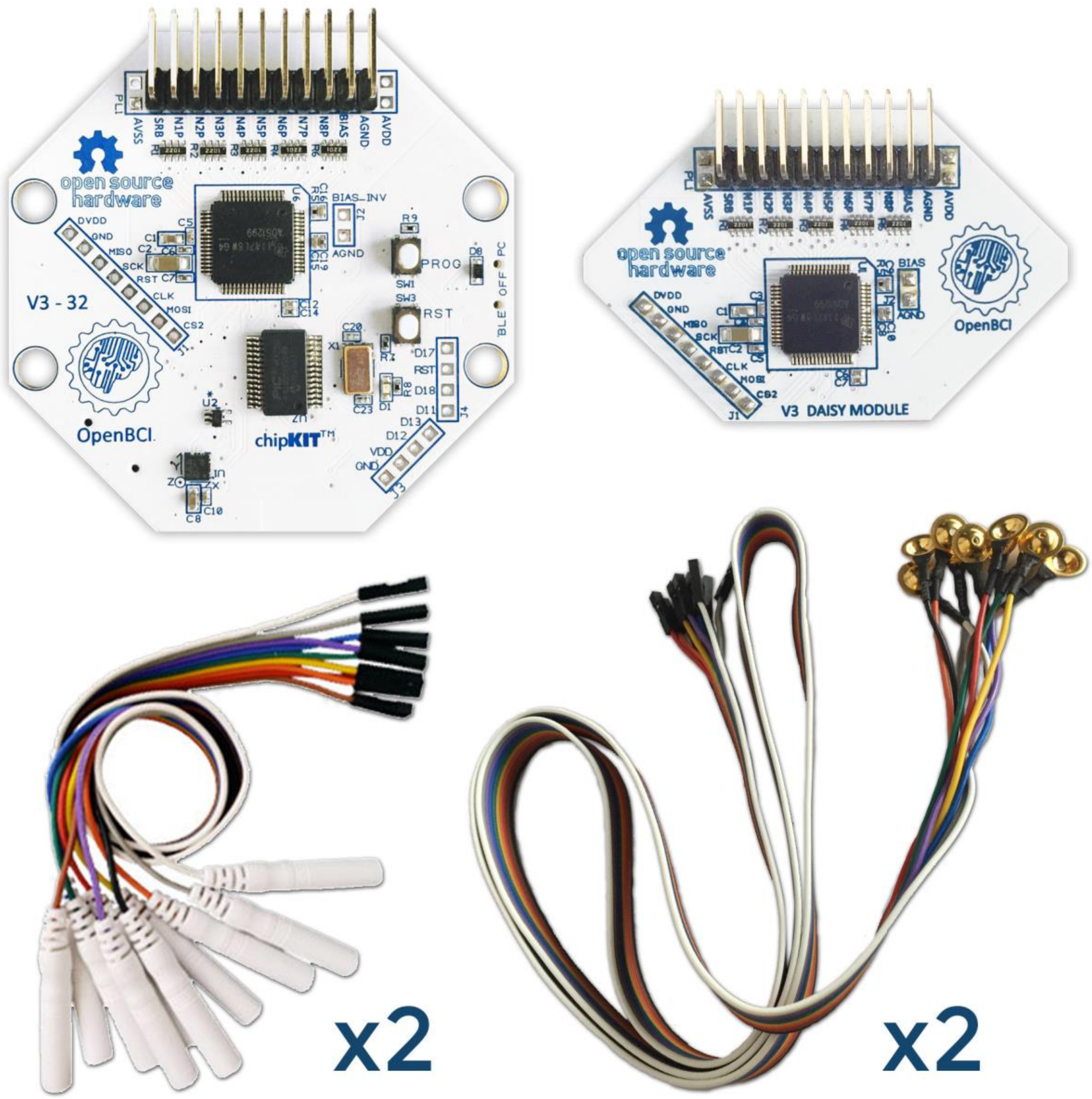

Figure 6-2. OpenBCI kit includes: microcontroller boards, USB dongle, gold cup electrodes and electrode adapters.[9]

[9] Source: http://openbci.com/

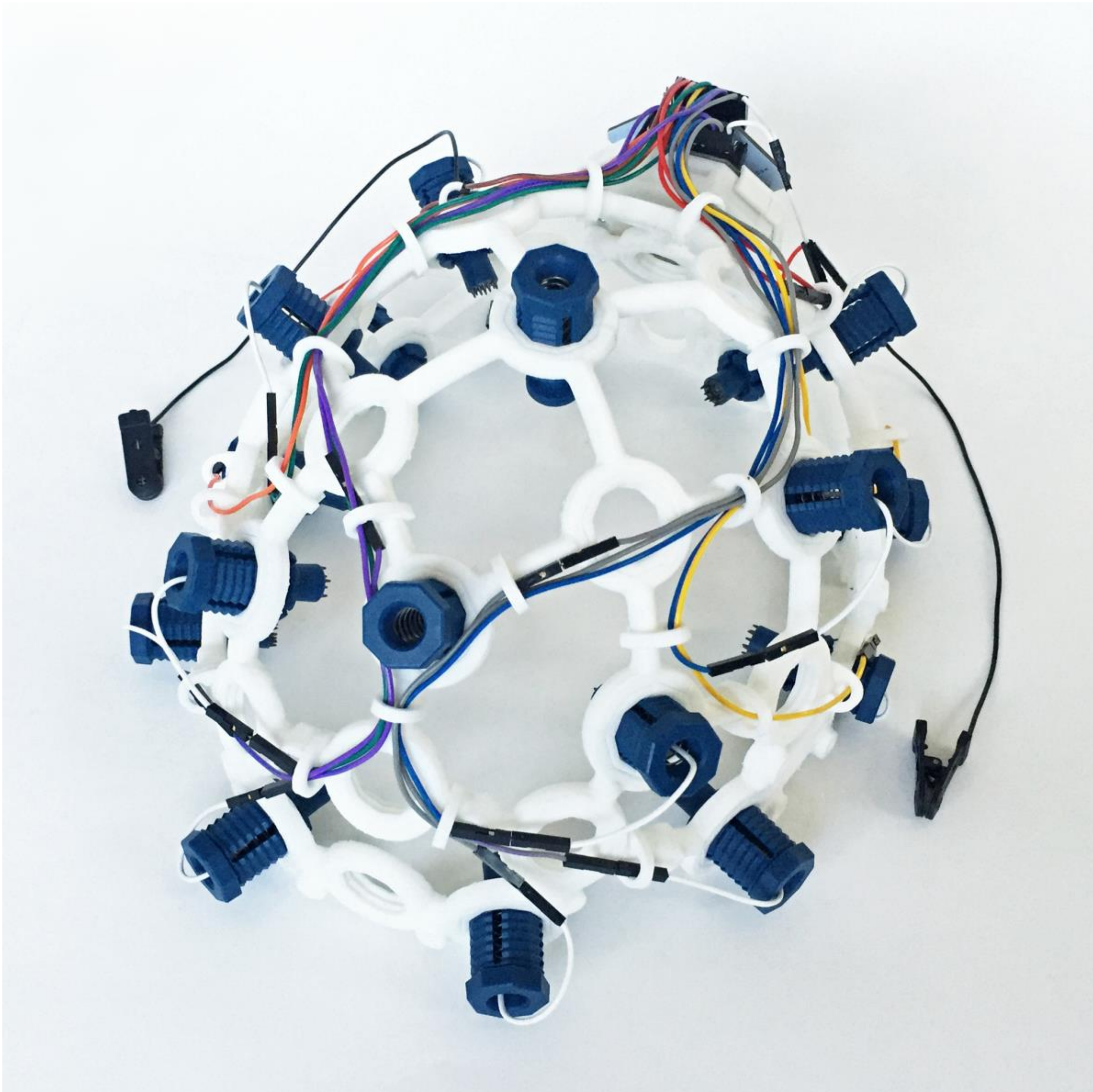

Figure 6-3. OpenBCI Mark IV Ultracortex EEG Headset[10]

[10] Source: http://openbci.com/

Figure 6-4. TDE-210 EEG electrode from Florida Research Instrument[11]

Figure 6-5. TDE-207 lead wire from Florida Research Instrument[12]

[11] Source: http://www.floridaresearchinstruments.com/

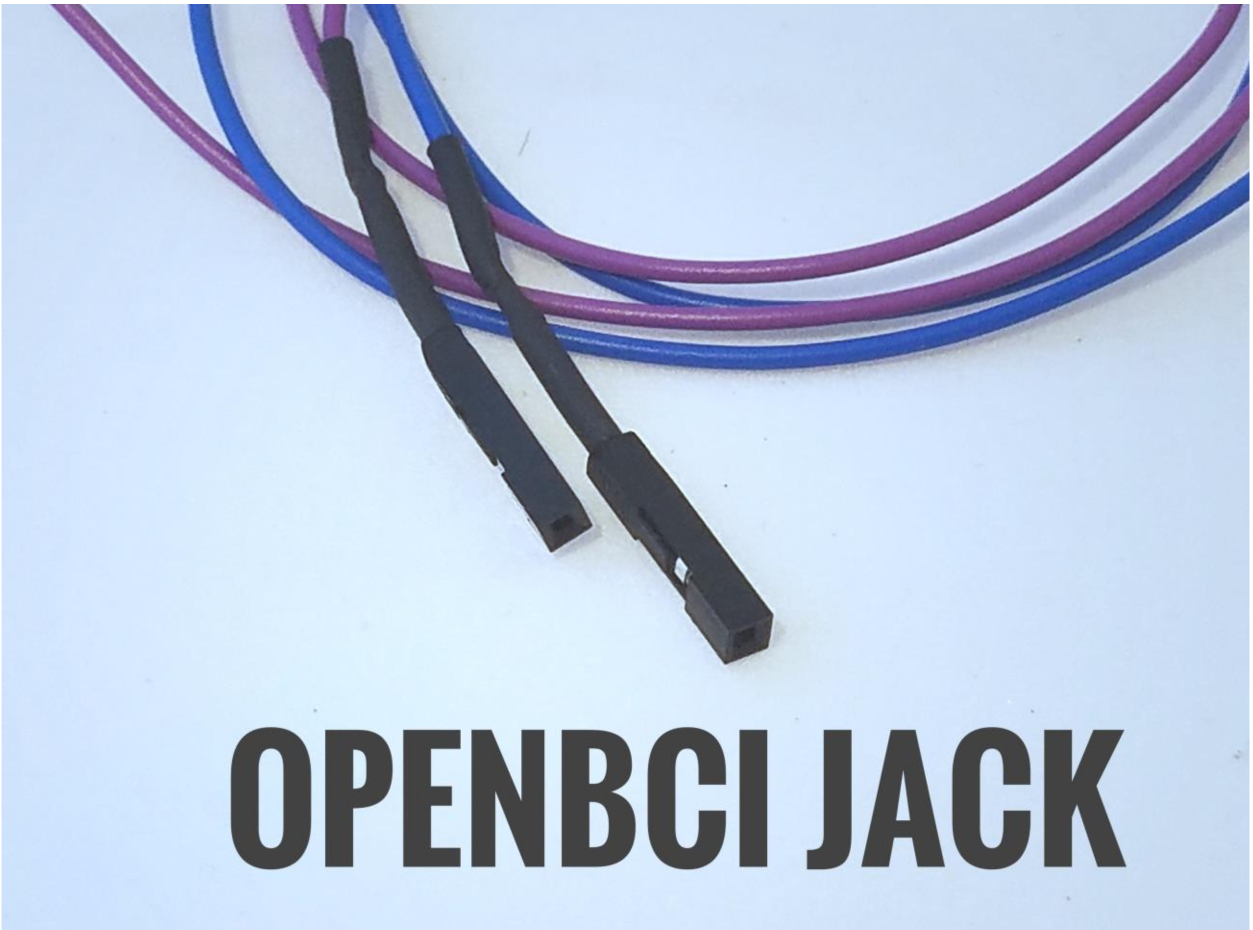

Figure 6-6. OpenBCI jack for lead wires and ear clips[13]

6.1.2 Software

The signal processing was handled using the OpenViBE software platform (Inria, 2015). It is a BCI software platform used to acquire, filter, process, classify and visualize brain signals. An OpenVibe scenario was created to measure relative Beta band power in which the power within the beta spectral band [13Hz - 30 Hz] was calculated and divided by the total power within the frequencies [4 Hz - 45 Hz] (Mühl et al. 2010). This normalized the data to result in values between 0-1.

[12] Source: http://www.floridaresearchinstruments.com/

[13] Source: http://www.floridaresearchinstruments.com/

Focus group participants were most interested in affective feedback applications and frontal lobe sensor locations. They were particularly interested in educational applications. Beta measurements can provide information about attention, alertness and active engagement in mental activity and can be obtained from frontal lobe sensors (Herrmann, n.d.). This was inline with focus group feedback for possible use cases, therefore a Beta task was seen as appropriate for the experiment task.

A threshold needed to be set to determine the appropriate Beta band power needed to move the drone forward. The method used by Mühl et al. (2010) was adopted to determine what that threshold number should be. Pilot studies were run with 10 people, across three simulation trials. The medians were evaluated from each pilot test, and an average was then taken. The threshold determined based on the pilot study was 0.1235. In order to move the drone, a participant's beta band power must be greater than 0.1235. Because Beta is measuring engagement and attention, participants were instructed to focus on a thought of their choosing and concentrate in order to increase their Beta and move the drone.

Once the OpenVibe environment acquired the raw EEG data, it was processed using the designed processing scenario. Afterwards it was passed to a python environment via the Lab Streaming Layer (LSL) protocol. LSL is a popular communication protocol due to its ability to stream, record, and analyze real-time time-series data (Kothe, 2014). The python environment featured functions that passed the processed data to firebase, a real-time database used to synch EEG data from OpenViBE to the simulation.

The database set up was also used to store the task completion times, while the web server hosted the simulation. LSL was a crucial step in enabled the real time data to be sent over the web. The pylsl library was used to receive the data stream from OpenVibe and send it out to Firebase, thus connecting the OpenBCI system to the Brain-Drone Race simulation.

6.2 Usability Study I - Investigating the Usability of the Ultracortex Mark IV OpenBCI Headset

In an attempt to get benchmark metrics and baseline specification, a usability study was performed using the Ultracortex Mark IV EEG headset from OpenBCI. The Ultracortex, seen in Figure 6-3, is a 3-D printed headset and is the default form factor sold by OpenBCI. During the benchmark testing, a medium (48-58 cm) sized headset was outfitted with the Cyton Board. This headset was chosen because it could utilize the same board that would be used for the final prototypes. Note, for this experiment, only EEG measurements were used. The sensor placement on the Ultracortex is in line with the 10-20 system, as seen in Figure 6-7. Although the 10-20 system is a highly recognized standard, not all commercial devices on the market utilize this system (American Electroencephalographic Society, 1994). For example, the Emotiv Insight does not follow the 10-20 system for it’s sensor placement.

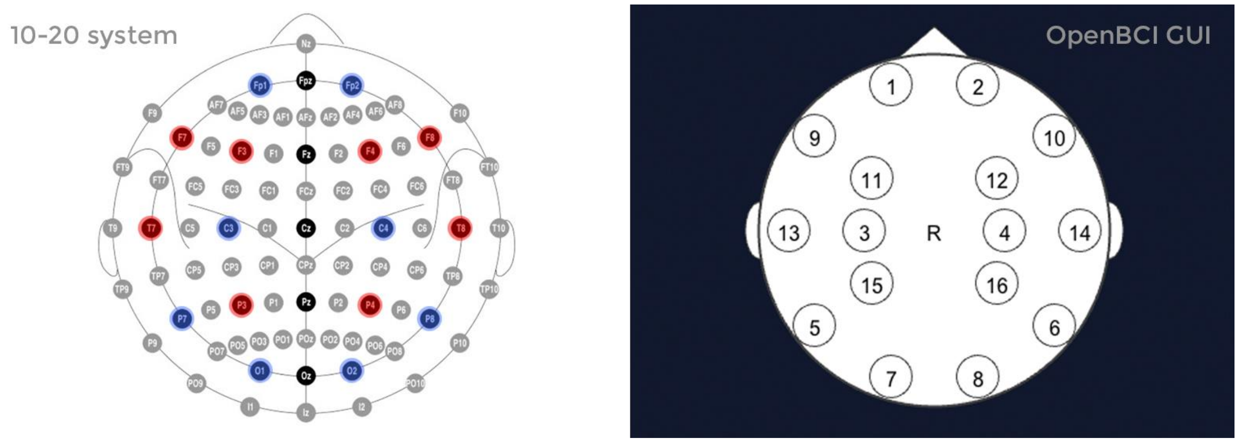

Figure 6-7. OpenBCI sensor placement and 10-20 system[14]

6.2.1 Participants

A total of 30 women between the ages of 18-30 participated in this study. The participant population was ethnically diverse with 24.24% African-American, 21.1% Asian or Asian American, 12.12% Hispanic or Latino, 39.39% Non-Hispanic White, and 3.03% other. The participants had various academic backgrounds, 14 were from engineering, 13 were from liberal arts and sciences one from health and human performance and one from agricultural and life sciences.

Even with non-technical backgrounds, 20 of the 30 participants had prior knowledge of BCI. Participants reported having participated in other BCI studies, taking a course, hearing about the Brain-Drone Race, learning about it from other peers, and reading online articles. Participants were asked about their level of knowledge of BCI as well. On a scale of one to five with one being no knowledge and five being very knowledgeable, 47.37% reported a two, 15.79% reported a three, 26.32% reported a four and 5.26% reported a five. The majority (n=20) of the participants in the study were wearable owners. The most commonly owned wearables were Apple Watches, Fitbits,

[14] Source: http://openbci.com/

and headphones. This supported the most commonly reported usage being fitness. Only three participants indicated that they use wearables five days a week, while four participants indicated they use wearables 7 days a week. When asked about their level of comfort with regularly wearing a device that is capable of sensing their brain waves, only 6 participants responded uncomfortable or very uncomfortable.

6.2.2 Experimental Design

The study was held at the University of Florida. The study setup can be seen in Figure 6-8. A monitor was used to display the electronic surveys and the Brain-Drone Race simulation. A mirror was used to allow participants to see themselves wearing the device. Audio and video devices were used to record each session. Finally, other existing devices were on site in case the participant had questions or wanted more information about other devices.

Figure 6-8. Experimental setup for usability study I (Photo courtesy of the author)

After signing consent forms participants were asked to complete a pre-survey. The survey asked basic demographic questions as well as investigated current wearable usage, familiarity with BCI technology and willingness to wear a wearable that can measure brain activity.

Following the pre-survey, participants were given a brief background on BCI technology, how it works, and some examples of non-medical use-cases. It was explained that the goal of the study was to examine the usability of the Ultracortex device. This study was designed after a study done at the University of Twente by (Nijboer et al., 2015). Usability was measured by task completion time, a user reported mounting time, and subjective post survey questions.

Following the explanation of BCI and the example use cases, users were asked to fly the Brain Drone Race simulator. They were given three practice attempts before the three "official flights". The completion times of the official flights were recorded and the average time was calculated. In order to motivate participants during the task, the participant with the fastest average time was given an additional $25 gift card. All participants were paid $15 for participation.

Following the task, a post survey was completed. The survey consisted of questions from the WEAR Scale, the CRS, and few additional Likert scale questions. The study concluded with a brief interview. The purpose of the interview was to give the participants an opportunity to elaborate on their responses, offer general feedback, and suggestions on future devices.

6.2.3 Results

Qualtrics and Microsoft Excel was used to aggregate the results and calculate the descriptive statistics. The slowest task completion time was 62.85 seconds, and the

fasted time was 32.25 seconds. On average participants completed the simulation in 52.34 seconds. The results from the post survey were analyzed based on the respective standard scales therefore, the CRS scores were analyzed together, the WEAR Scale scores were analyzed together, and the additional BCI specific questions were analyzed separately.

The CRS is a tool that measures wearable comfort across six dimensions: emotion, attachment, harm, perceived change, movement, and anxiety (Knight and Baber, 2005). The tool has been used to evaluate various types of wearables including BCI devices. The general comfort descriptors to describe each dimension can be seen in Table 6-1. Users were asked, “To what extent do they agree or disagree” with the statements in Table 6-2. The scale uses a 21-point Likert scale to measure each dimension. For more information on the development and validation of the CRS, see (Knight and Baber, 2005).

Table 6-1. General Comfort Descriptors, CRS Groups

Group	Description
1	Emotions, concerns about appearance and relaxation
2	Physical feel of the device on the body, attachment
3	Physical effect, damage to the body
4	Feeling physically different, upset
5	The device physically affects movement
6	Worry about the device, safety, and reliability

Table 6-2. Comfort Rating Scale Definitions

Group	Description
Emotion	I am worried about how I look when I wear this device. I feel tense or on edge because I am wearing the device.
Attachment	I can feel the device on my body. I can feel the device moving.
Harm	The device is causing me some harm. The device is painful to wear.
Perceived Change	Wearing the device makes me feel physically different. I feel strange wearing the device.
Movement	The device affects the way I move. The device inhibits or restricts my movement.
Anxiety	I do not feel secure wearing the device.

Because the CRS is a 21-point Likert scale, the median score was an 11. Any score above the median was seen as overall agreement with the statements. Because the statements were worded with a negative sentiment, a high score meant a general negative sentiment toward the device. The mean CRS score response across all participants was an 11.19 with a standard deviation of 3.81, which was practically neutral. On average, participants did not feel strongly positively or negatively about the device.

However, Table 6-3 shows CRS responses broken down by the groups. From this chart it was determined that participants did feel negatively in regards to emotion, attachment, and perceived change, with CRS scores of 13.23, 15.12, and 12.43 and standard deviations of 5.48, 5.37, and 6.40 respectively. This is particularly interesting because based on the definition of emotion and perceived change in Table 6-2, these metrics relate to socially acceptability and appearance.

Table 6-3. Comfort Rating Scale Score by Group

Group	Average
Emotion	13.23
Attachment	15.13
Harm	10.23
Perceived Change	12.43
Movement	8.80
Anxiety	7.30

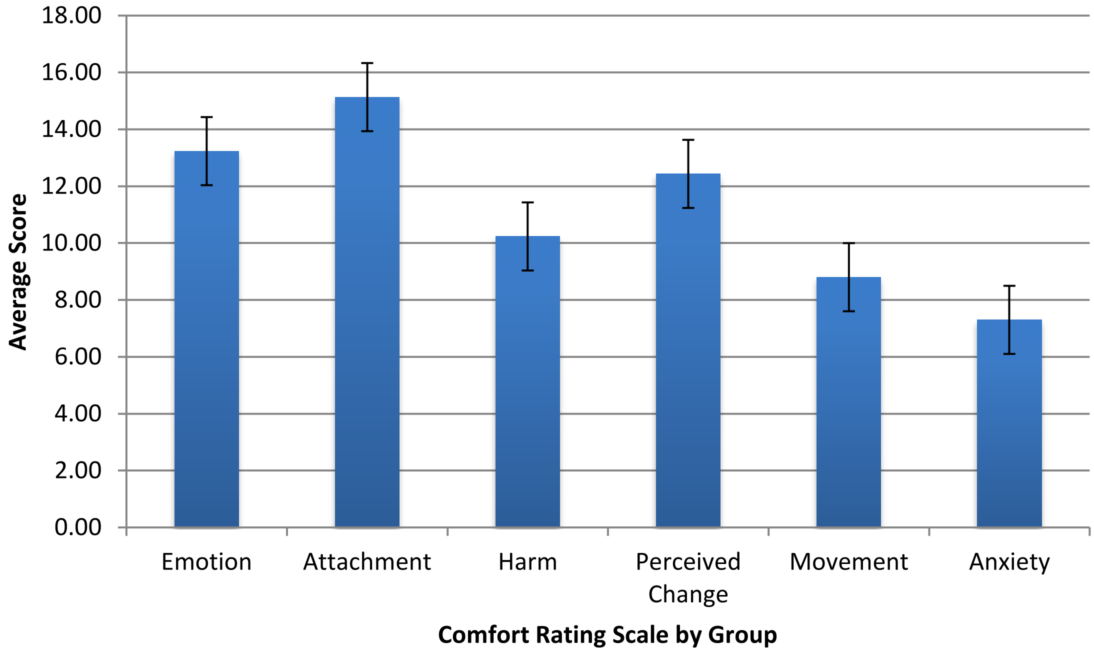

Figure 6-9. Comfort Rating Scale averages by group

The WEAR Scale was developed by Norene Kelly at the University of Iowa. This scale, comprised of 14 questions, was designed to consider the unique factors that affect wearable acceptability as opposed to just technology acceptance. Some of these factors include: context of use, habits of dress, fashion, form, and aesthetics (Kelly and Gilbert, 2016). It is intended to measure and predict the social acceptability of wearable devices or prototypes. A nine- step process based on (DeVellis, 2012) was used to validate the scale. The full validation and creation process can be reviewed in (Kelly and Gilbert, 2016). The creator recommends using a six point Likert scale (Strongly Agree=6, Agree=5, Somewhat Agree=4, Somewhat Disagree=3, Disagree=2, Strongly Disagree=1) to answer the 14 questions seen in Table 6-4. *Note items denoted with an "R" are reversed scored*.

Table 6-4. WEarable Acceptability Range Scale

#	Statement
1	I like what this device communicates about its wearer.
2	I could imagine aspiring to be like the wearer of such a device.
3	This device is consistent with my self-image.
4	This device would enhance the wearer’s image.
5	The wearer of this device would get a positive reaction from others.
6	I like how this device shows membership to a certain social group.
7	This device seems to be useful and easy to use.
8	This device could help people.
9	This device could allow its wearer to take advantage of people. R
10	Use of this device raises privacy issues. R
11	The wearer of this device could be considered rude. R
12	Wearing this device could be considered inappropriate. R
13	People would not be offended by the wearing of this device.
14	This device would be distracting when driving. R

Unlike the CRS statements, the WEAR Scale statements are mostly positively worded. However, there are four statements that are worded negatively and the scoring was reversed during analysis to account for the wording. Because the WEAR Scale is a six-point Likert scale, 3.5 was taken as the median. Scores above 3.5 were perceived as agreement and a positive sentiment, where as scores below were perceived as disagreement and a negative sentiment. Similar to the CRS results, the average WEAR score response across participants was a 3.51 with a standard deviation of 0.63, which is right at the median response. Participants did not feel generally positively or negatively about the device.

Table 6-5. WEAR Scale results by statements

Statement	Average Score
I like what this device communicates about its wearer.	3.73
I could imagine aspiring to be like the wearer of such a device.	3.23
This device is consistent with my self-image.	2.27
This device would enhance the wearer's image.	2.03
The wearer of this device would get a positive reaction from others.	2.33
I like how this device shows membership to a certain social group.	2.43
This device seems to be useful and easy to use.	3.67
This device could help people.	5.20
This device could allow its wearer to take advantage of people. R	4.67
Use of this device raises privacy issues. R	3.73
The wearer of this device could be considered rude. R	5.03
Wearing this device could be considered inappropriate. R	4.30
People would not be offended by the wearing of this device.	3.37
This device would be distracting when driving. R	3.17

Based on the results shown in Table 6-5, there were a few statements that received below median scores and therefore add to the negative perception. Again, the statements that received a negative sentiment relate to social acceptability, appearance, and usability.

In addition to the standardized questionnaires, the following five custom questions were added to the post survey:

1. How likely are you to wear this device in public?
2. How socially acceptable would you say this device is?
3. How comfortable was this device to wear?
4. How easy was this device to setup?
5. How was the speed of setup for this device?

A five-point Likert scale, with a median of 2.5 was used for responses to these questions. The average responses from questions one through three were 2.03 (σ = 1.00), 2.37 (σ = 1.00), and 2.27 (σ = 0.91) respectively. Therefore people were generally unlikely to wear the device in public, felt that it was unacceptable, and was uncomfortable. The average responses to questions four and five were 3.50 (σ = 1.17)

and 3.67 (σ = 0.88) respectively. Therefore people generally thought the device was easy to set up and that setup was fast. However, as with the other scales, the sentiment towards the device was negative for the metrics that pertain to social acceptability.

It should be noted that for this usability study, only two forehead sensors were used, if all of the sensors were used and needed to be receiving a “good” signal, the actual setup time and the perceived setup time would most likely have been different. In fact, due to certain hair lengths, textures, and styles, some participants would not have been able to participate if all 8 channels were used to capture data. Figure 6-10 shows a participant wearing the Ultracortex device. During the experiment, nine of the participants had to change their hairstyle to wear the device. Most of these participants had top buns or medium to high ponytails. Other hairstyles that proved to be cumbersome during set up were, afros, and braids. One participant also expressed concern that the device may not fit her head. The OpenBCI headset is made of rigid 3D printed material. It is not flexible or adjustable, therefore it can be difficult to accommodate certain hairstyles, head shapes, and head sizes.

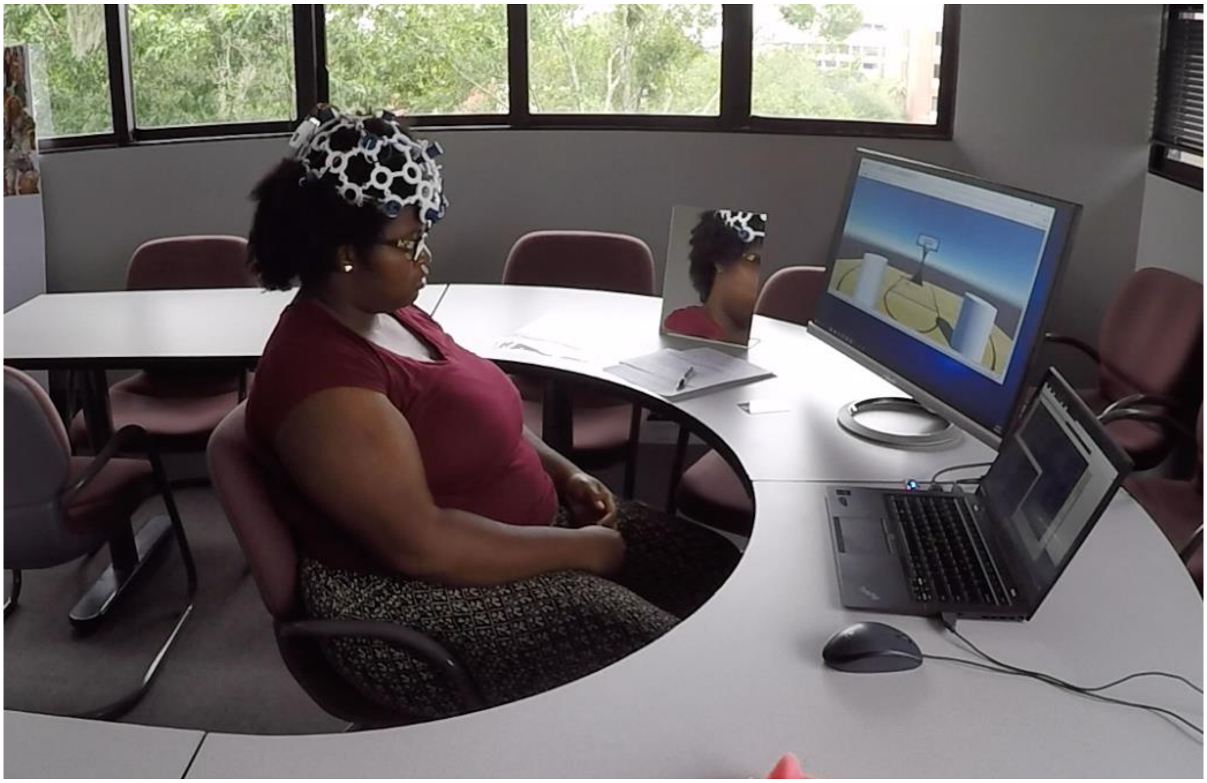

Figure 6-10. Participant from usability study I wearing OpenBCI Mark IV headset (Photo courtesy of the author)

The post interview was used to give participants an opportunity to offer open-ended responses. This was also an opportunity to check for inconsistencies between quantitative survey results and qualitative interview responses. In general, participants were more lenient on the survey responses. They were more critical of the device in the post interview. The following are snippets from post interviews:

FJ: How did you feel about the way the device looked?

U1: I probably wouldn’t wear it in public. Just because it’s not normalized

FJ: Do you have any feedback on the design? If you thought this device was cool and some of the use cases were interesting, how would the device have to look for you to be interested in wearing it?

U1: For out in public probably hidden, disguised I guess, maybe a headband or a hat or something. You could wear a hat over it

FJ: What did you think about the device?

U2: I thought it was a little bit uncomfortable on the front of my head after a long time, if I wore that um for hours it'd probably irritate me and I'd want to take it off.

FJ: Would you wear it in public?

U2: Probably not for an everyday use, but if I had to and if for some reason or another if I needed to, then I wouldn't mind it but I would probably not wear it out in public?

FJ: Do you think that its socially acceptable?

U2: Probably not

FJ: Why not?

U2: Because it's really um intrusive on the eyes, it really stands out a little too much distracting

FJ: Do you have any additional comments or feedback?

U2: I didn't know there were clips on the side that was new to me. I was not expecting the clips

FJ: If you were to wear a device everyday, what would you prefer that it looked like?

U2: I can see myself doing like a headband, that's probably about it, if it was for this part of my body (head)

FJ: A headband like this type (forehead band) or a headband that looks more like the ones you're already wearing?

U2: Yea a stylish, colorful, one that looks like a regular girls headband

FJ: What did you think about the device overall?

U4: So the device itself, the physical device is uh a bit uncomfortable on head so especially the front part and the setting it up I don't know if it's always like this like time consuming but setting it up to work was a bit time consuming

FJ: If you had to think about something that you would wear on your head, let's say you thought one of the use cases was very interesting and you would be interested in utilizing that, what would it need to look like for you to be comfortable wearing it on your head?

U4: Yea, maybe it can be like something with a style as you wear everyday like a headband or just some I don't know how to say but like a headband but something that is more acceptable right now so and its like beautiful to wear and it won't be like something extra on your head?

FJ: What did you think about the device?

U5: It was a little bit uncomfortable because I had some marks on my forehead after and it caused some pain, but other than that it was cool.

FJ: Would you wear it in public?

U5: Probably, yea. It's a good conversation starter. You can find lots of friends

FJ: Do you think that it's socially acceptable?

U5: Socially acceptable? I think that it causes some privacy issues

FJ: What do you mean?

U5: Because if these devices become common there are lots of issues with Fitbit and all of these kinds of devices if they are connected to internet so big brother.

FJ: Do you think it's socially acceptable?

U6: Umm yes and no. I mean this day and time like if it was in a class room, yea it would be accepted but just to walk around with it, people might be "oh my God, what is that?"

FJ: So if you wanted to have a device that could sense your EEG and track your cognitive activity and you wanted a device that you would be willing to wear regularly in public what would it need to look like for you to be comfortable wearing it?

U6: I think something small, smaller, something more presentable, like how Fitbit is, its multiple Fitbit, different colors, different bands, customizable

FJ: So you wouldn't just regularly wear it like you wear your Fitbit?

U7: No, naw

FJ: Why not?

U7: Because it looks like that helmet thing. It reminds me of something that someone had to wear because they were sick or had something wrong with them

FJ: Would you be willing to wear something in your hair?

U9: Oh yea definitely

FJ: What did you think about the mounting experience?

U9: Its cumbersome, because my hair is very fluffy, so you have to like smoosh my hair down and get it in the right spot and make sure its not going to fall or lean

or whatever. It kind of feels like a helmet, like putting on a bike helmet or something like that except there aren't really straps to really keep it still so, I couldn't imagine, that would make it even more weird. It would be awkward trying to walk around with something like that on my head.

FJ: So you wouldn't wear it in public?

U9: No

FJ: Do you think its socially acceptable?

U9: I think people would look at me and be like why are you, like what is that on her head, why is she wearing that? They might think that something is wrong with me or that maybe I'm sick. I think that I would get a lot of looks and questions.

Although the OpenBCI device averaged neutral ratings across both standardized scales, the device received negative responses on the metrics that relate to social acceptability, social message, and appearance. Additionally, the participants expressed negative sentiments towards the device during the post interview with regards to social acceptability and a willingness to wear. A second and final usability study was performed to evaluate the three prototype devices. The second usability study mimicked the first study design.

6.3 Usability Study II - Investigating the Usability of Three Wearable EEG Headbands

The final phase of this research involved a with-in subject usability study. The findings from all the previous steps of the UCD process informed the design and fabrication of three BCI headband prototypes. The purpose of the study was to determine user preference and evaluate the overall usability of three BCI prototypes. The results from this study were also compared with the results from the first usability study that evaluated the Ultracortex Mark IV OpenBCI headset. The study took place in an innovation room on Intel's Jones Farm Campus.

6.3.1 Participants

30 females between the ages of 18-30 were recruited to participate. The participant pool was diverse and relatively evenly distributed. Out of the 30 females, 5 identified as Asian or Asian American, 10 as Black or African-American, and 13 as Non-Hispanic White. While, most of the participants were STEM professionals (n=14), there was a mix of Intel and Non-Intel Employees as well as some students from local universities. Non-stem professions were categorized as business/finance (n=5), design (n=4), UX (n=4), healthcare (n=1) and student (n=2). More than half (n=16) of the participants reported having heard of BCI from friends, general conversation, the internet or school. Some reported having actually worn devices previously. 60% of the participants own wearables and over 50% wear them everyday. This is double the nation average of 25% in 2017. The large number of wearable users is likely due to the selected target population. This age range was chosen as they represent early adopters and the target age for new technology, therefore it is not surprising that a large percentage own wearables (Patel, 2017). The most popular wearable items were the Apple Watch and Fitbit, which support the data that shows 61% of their usage is for fitness. None of the participants reported being very uncomfortable with regularly wearing a device that can measure their brain activity. The majority, 53% reported being neutral toward the idea, and %16 (n=5) reported being uncomfortable.

6.3.2 Experimental Design

The experimental set was very similar to the first usability study. A monitor was used for the drone simulation experience. During this experiment, the prototype devices were on display, as well as the existing devices and info pages used in the first focus group. A mirror was used to allow user to see themselves with the devices on. Other

visual aids used during the experience included, the one-pages from the iterative design focus group and non-EEG enabled headbands that were similar to the prototypes.

6.3.3 Procedure

Participants were asked to sign consent forms and take a Qualtrics pre-survey before the session began. The sessions begin with an overview of BCI and some brief background information. The problem statement and purpose for the research was explained. Participants were introduced to three products that are currently on the market; Smart Cap, Mindrider helmet, and Kokoon headphones. In additions to the existing examples, other potential use cases were explained. The info pages for existing devices (Figure 4-2) were shown as well as actual BCI devices (EPOC, Muse, Neurosky Mindwave, Focus, and Insight). Finally the research process that led up to the final study was discussed. Users were informed of the focus groups, some of the key insights, and the goal of enabling headwear for women with EEG technology. The 4 one-pagers from the design focus group that were chosen to prototype were discussed. The one pager for the traditional headband, forehead headband, transferable sensor plate and interchangeable face plate were used as an introduction to the prototypes and can be seen in Figure 5-2, Figure 5-3, Figure 5-6, and Figure 5-7.

Following the introductory conversation and background information, participants were asked to fly the Brain-Drone Race simulator with each prototype. The order in which they received each prototype was counterbalanced to account for ordering effects. Each prototype was introduced and a description of how the final product would differ from the prototype was explained. For example, all of the prototypes had wires, the final devices would be wireless. After the prototypes were introduced and mounted on the participant's head, they were allowed to practice flying the simulation before the

timed flights began. Everyone was given three timed attempts with each prototype. There was a post-survey following each device. It was more appropriate to do the survey immediately instead of waiting until the end to do a survey on all three devices at once in an effort to avoid participants forgetting how each prototype felt and how they looked wearing each one.

During the survey, participants were asked to consider the final wireless product design and to ignore the OpenBCI board, ear clips, and wires. Two participants walked out of the session with the board and ear clips attached to them, meaning they must have been easy to ignore or forget about. The post survey consisted of the same primary information that was asked in the first usability study. The post survey included the CRA Scale, the WEAR Scale, and a few BCI specific questions. A brief follow up interview was conducted, after each survey. The follow up interview was to get open-ended qualitative feedback and to reiterate key ideas from the survey. This was done in an attempt to identify when participant's survey responses did not truly represent how they felt, if there was confusion with the survey question or if they forgot to disregard the ear clips and wires that would not be apart of the final device. One participant reported in the post interview that she responded in terms of BCI in general and not the specific device she was wearing. The post interview allowed her to adequately articulate her feedback for the specific device. Once all of the prototypes were used, participants were asked to rank the devices in order of preference. This information can be used to determine which prototype would be most suitable to move forward to be productized or for further testing and development.

6.3.4 Device Preference and Feedback

The letters A, B, and C were used to label the final three prototype ideas as seen in Table 6-6. That nomenclature will be used throughout this document to report results.

Table 6-6. Prototype nomenclature

Letter	Prototype Name
A	Traditional Headband
B	Transferable Sensor Plate
C	Interchangeable Face Plate
D	Ultracortex Mark IV Open BCI Device

In general the same number of participants (A=12, B=12, C=6) ranked Device A and Device B as their first choice. Slightly more participants (A=5, B=11, C=14) ranked Device C as their second choice. Again, slightly more participants ranked device A as their third choice (A=13, B=7, C=10). Participants either really liked A, ranking it as their first choice, or they really didn't like it and ranked it as their third choice. Many users expressed that although the device was socially acceptable it was not their personal style. Some user reported the traditional headband as being juvenile and reminding them of their high school style and even childhood.

The most common ranking order was BCA. Followed by ABC and ACB. A point system was used to analyze the data. As participants were asked to rank each device as their first, second, or third choice, three points were associated with each first choice vote, two points with second choice votes, and one point with third choice voice. The total points for each prototype was tabulated. The most popular device was B, the transferable sensor plate with a total of 65 "points", while A and C were not far behind with 59 and 56 "points" respectively.

> [P2.28] "All three of them are pretty easy to just forget about while I was wearing them. They are all so good that it kind of just comes down to the style preference. I think my style is just closer to the second one [B]."

6.3.5 Transferable Sensor Plate (B)

The transferable sensor plate, as seen in Figure 5-10, appealed to people because they liked the idea that it was concealable. It was appealing to women who didn't mind wearing a nice forehead headband, particularly a fabric headband, as well as women who prefer to wear hats. The final product is envisioned to be small, thin and easily concealable under other hats and headbands. The design could utilize conductive ink sensors similar to the Muse device.

> [P2.3] "I really love the concept of being able to conceive it, because if we are talking women's fashion, nowadays there are so many options so many outfits, so many expressions of who you want to be, who you want to look like that having a static thing will only be useful with certain outfits. You are very limited in that sense, so in terms of versatility, this [B] one wins to me."

> [P2.4] "Truly customizable"

> [P2.1] "I look fantastic"

> [2.6] "Can I take it home?"

Limitations: A few users did offer the feedback that it would be cool if the transferable sensor plate were not a full headband and could attach to various headbands, scarves and hats. Once the discussion continued to the idea of potentially permanently retrofitting their accessories to be able to attach to the sensor plate, they no longer liked that idea and favored a headband. This presents an interesting engineering challenge that could be future work. This could be an opportunity to collaborate with mechanical engineers, industrial designers and material science engineers to understand what types of non-destructive attachment mechanisms could be created that would work with various textiles and not snag users hair. At first glance Velcro might seem like a solution, but focus group participants expressed their fear of

putting Velcro near their hair as well as the fact that when a user is not wearing the sensor plate but is wearing their accessory the Velcro may aggravate the skin. For now, a thin elastic headband was used to prototype the idea.

6.3.6 Traditional Headband (A)

The traditional headband was favored by some participants for being flexible, lightweight and comfortable. Many participants reported not being able to feel it and forgetting they were wearing the device. The comb sensors were able to penetrate various hair types as well as the wigs that participants were wearing. Most users felt that the traditional headband would not hinder their hairstyle or outfit and would be willing to wear it. However, a few users did say that it did not match their personal style. Some users compared it to something they would have worn in high school and was not their preferred look although every participant felt it would be socially acceptable.

> [P2.2] “I like the minimalist simplicity of it, and that will go with anything.”

> [P2.5] “I like the application of it, it’s flexible, it just slides on.”

> [P2.7] “This one is great because you could wear it everyday and people would just think, this girl really likes headbands. You get that Blair Waldorf look going on”

> [P2.13] “I think for my hair type [curly wig] it is socially acceptable because it is well hidden”

Limitations: Unlike the other prototypes this headband does not have an elastic strap. Three participants expressed concern about the headband not being secure and potentially falling off. Because the headband used was extremely flexible and could be molded to a user's head, it does not fit tightly if it is not formed on the head. Even when it is form, it still would not be as tight as an elastic band. Not only was this noticeable for some users, this is also important to consider when thinking of sensor contact over time.

If the headband is not secure enough on the head, the signal could become weak. This was not observed in the study, but a consideration for longer term usage. Only one user reported the comb sensors being a little uncomfortable. This participant had noticeably fine hair, which may have been a factor in why she was able to feel the combs or felt more discomfort than other users. The comb sensors on a final device need to be strong enough to penetrate thick hair but gentle enough to not cause discomfort for users with more fine hair.

6.3.7 Interchange Faceplate (C)

This was the most popular second choice. Many users reported this as being easy to wear and pretty. The idea of customizing the band resonated with all of the user. There were a surprising number of participants who stated that they don’t typically wear forehead headbands, but seeing themselves in the prototype inspired them to try it out in the future. Other users reported that they don’t typically wear forehead headbands, but that they would consider it if they wanted the EEG data. Even the participants who shared that it was not their style and that they would likely not wear it, indicated that the device was socially acceptable.

Outfit centric and customization were two of the top insights from the focus group and prototype C addressed both of the issues. Most participants stated that it would not hinder their hairstyle and they would even be willing to style their hair around it. Additionally, most participants stated that it would not hinder their outfit, because they could change the design when necessary

> [P2.12] “I like how it is more customizable. I would not buy a device that looks the same everyday”

> [P2.20] “This one is fashion. I can wear it alone and I wont feel like something weird is on my forehead, it’s like an accessory”

> [P2.19] "Great. I liked it. The device itself was really fancy"

> [P2.29] "I like this one, it's something I could see myself wearing. It wouldn't look like you're wearing something weird on your head. These things [existing devices] are weird"

Limitations: Similar to prototype B, some participants stated that they didn't normally wear forehead headbands but would consider trying it. Participants with bangs were not as favorable of the idea of the forehead headband, although they did like the customization feature. In general, this option got a lot of positive feedback but B was favored slightly higher because participants liked the idea of wearing something different. Although C was customizable, it is still the same forehead headband all the time. Whereas B, allows user to wear hats, headbands, and other head worn accessories they already own. Finally, more consideration needs to be given to the attachment mechanism for the faces. What mechanism would afford for the most user friendly and seamless attaching and detaching process, while preserving a sleek design? Also, consideration for how alternative faces can be created should be given some thought. One participant even mentioned the desire to make her own face plates.

6.3.8 Quantitative Results and Analysis

Similarly to the first usability study, responses to the CRS, WEAR Scale, and custom questions were analyzed for each device. Table 6-7 – 6-9 show the mean survey responses across participants for each device.

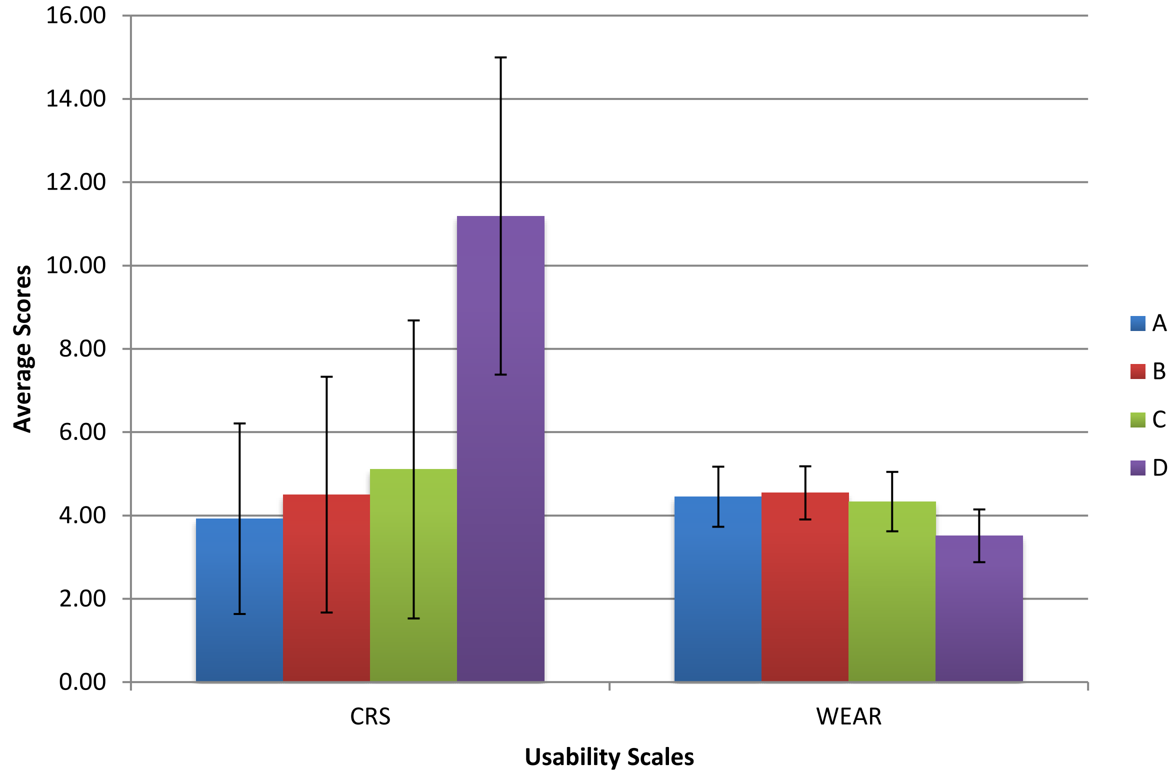

Figure 6-11. Average CRS and WEAR Scale responses by device

Table 6-7. Average CRS and WEAR Scale responses by device

	Device			
	A	B	C	D
CRS	3.92	4.50	5.11	11.19
WEAR	4.45	4.54	4.33	3.51

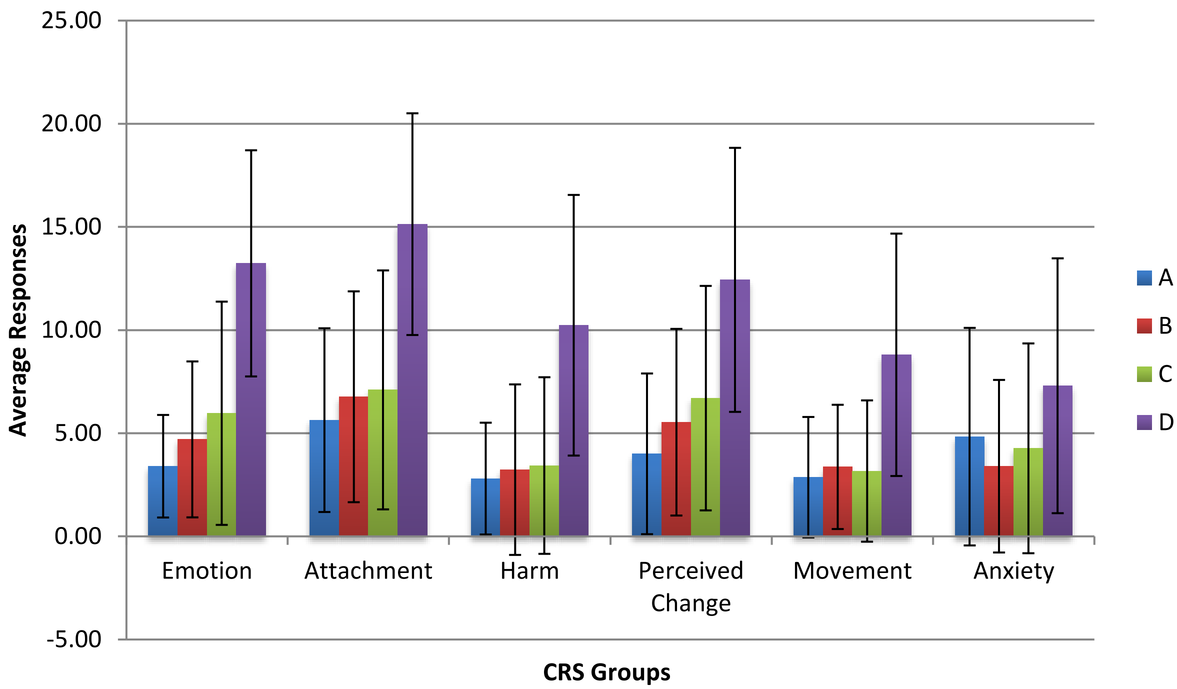

Figure 6-12. Average CRS group responses by device

Table 6-8. Average CRS group responses by device

	Device			
	A	B	C	D
Emotion	3.40	4.70	5.97	13.23
Attachment	5.63	6.77	7.10	15.13
Harm	2.80	3.23	3.43	10.23
Perceived Change	4.00	5.53	6.70	12.43
Movement	2.87	3.37	3.17	8.80
Anxiety	3.40	4.70	5.97	7.30

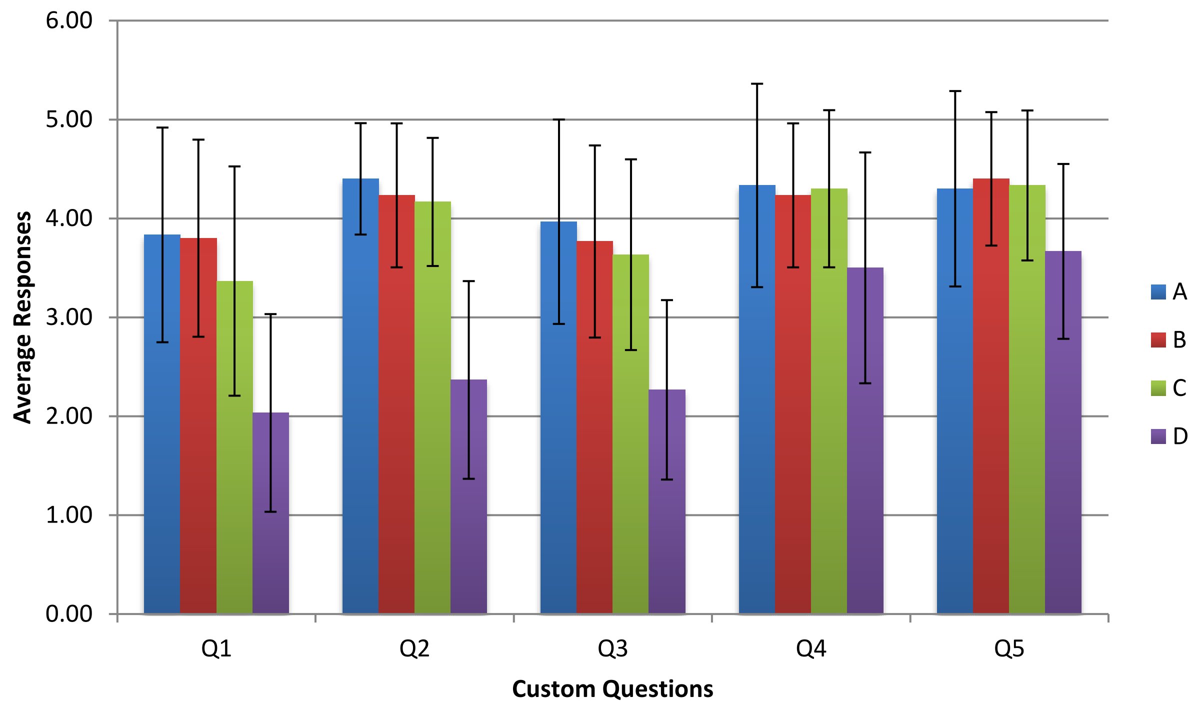

Figure 6-13. Responses to custom questions by device

Table 6-9. Responses to custom questions by device

	Device			
	A	B	C	D
Q1. How likely are you to wear this device in public?	3.83	3.80	3.37	2.03
Q2. How socially acceptable would you say this device is?	4.40	4.23	4.17	2.37
Q3. How comfortable was this device to wear?	3.97	3.77	3.63	2.27
Q4. How easy was this device to setup?	4.33	4.23	4.30	3.50
Q4. How was the speed of setup for this device?	4.30	4.40	4.33	3.67

Because the CRS is a 21-point Likert scale, the median score is 11. Because the wording of the statements in the scale are negative, responses below the median that are in disagreement with the statement are taken as positive responses and positive sentiment toward the device. Based on Table 6-6, it can be concluded that all three devices performed well on the CRS scale because the responses are well below the median. Although B was chosen by users as the most desired, A performed slightly better on the CRS. When considering the CRS groups that correlate to social

acceptability (Emotion and Perceived Change), A performed the best, but all the devices were well below the median of 11.

The WEAR Scale on the other hand, had positively worded statements and a median of 3.5. All of the devices performed well on the WEAR Scale with C performing slightly better. The median for the custom questions was 2.5 and above the median is considered positive. All of the devices received positive responses on all the metrics.

As a reminder, participants' responses to the OpenBCI device were right at the median number on the CRS and the WEAR Scale. The OpenBCI device only performed above the median on two of the custom question metrics. Therefore all three of the prototypes outperformed the OpenBCI device on the user satisfaction metrics.

The average task completion time for devices A, B, and C were 24.27 seconds (σ=2.02), 24.67 seconds (σ=2.58), and 24.65 (σ=2.33) respectively. Figure 6-13 shows that these results were right under half of the average task completion time for the OpenBCI device, 50.34 seconds (σ=3.32). The three prototypes out performed the OpenBCI device on every usability metric.

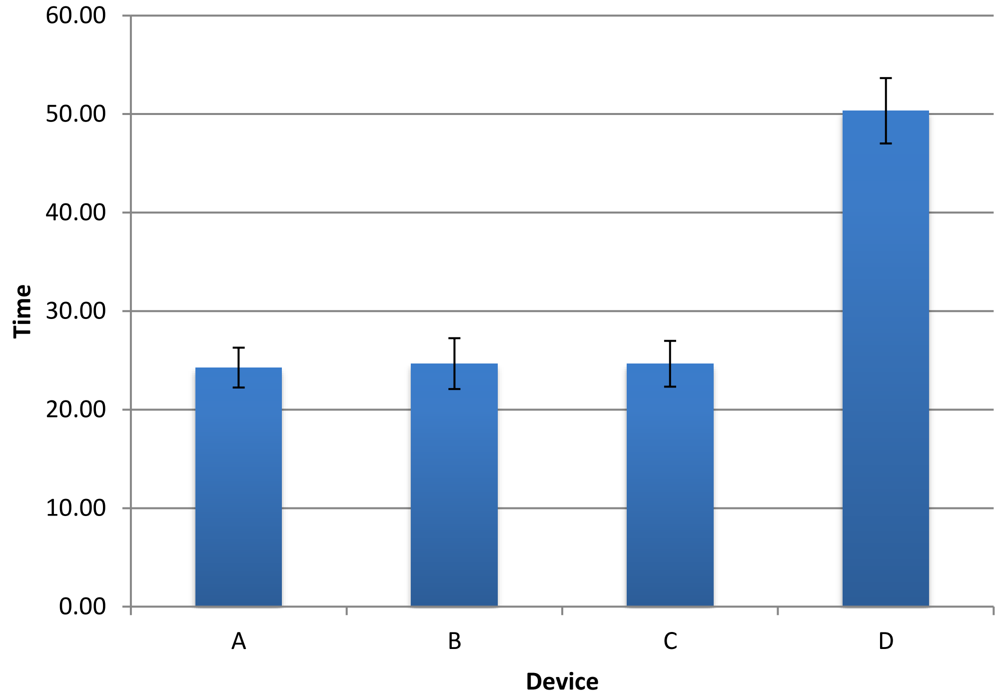

Figure 6-14. Average task completion time by device

Statistical analysis was used to validate the observed results. Because participants in the first usability study were not involved of the second usability study, their responses could not be included in the repeated measures ANOVA used to compare the three device prototypes. However, because the goal was to design a better BCI with regards to usability and social acceptability, a paired t-test was used to compare one of the new devices against the OpenBCI device.

A one-way repeated measures ANOVA was used to analyze the overall difference between devices A,B, and C. The repeated measures analysis took into account participant responses to the CRS, WEAR Scale, and the two Likert questions investigating mounting. Additionally, a Bonferroni correction was used. According to the pairwise comparison table, there was no significant difference between devices A and B ($p = 1.0$, $\alpha = 0.05$), devices A and C ($p = .371$, $\alpha = 0.05$), or devices B and C ($p = 0.412$,

$\alpha = 0.05$). The experiment was counterbalanced and no ordering effects were observed. Of the five variables, device C performed slightly lower on two and was only 0.02 seconds faster than device B for average task completion time. Taking that into consideration as well as it being the least preferred device, it was selected to be compared to the OpenBCI device. The goal of the study was to design 3 more socially acceptable BCI devices, if the lowest performance device is significantly better than the OpenBCI, the better performing devices will be as well. A two-sample t-test was used to compare means from devices C and D and test the following hypotheses

H_0: There is no significant difference in task completion time across devices
H_1: The task completion times for device C is significantly lower than device D

H_0: There is no significant difference in users' reported ease of mounting across devices
H_1: The user reported ease of mounting for device C is significantly higher than device D
H_0: There is no significant difference in users' reported speed of mounting across devices
H_1: The user reported speed of mounting for device C is significantly faster than device D

H_0: There is no significant difference in CRS scores across devices
H_1: The CRS score for device C is significantly higher than device D

H_0: There is no significant difference in WEAR Scale scores across devices
H_1: The WEAR Scale score for device C is significantly higher than device D

Device C was significantly faster than device D ($t = 25.41$, $p = 0.000$, $df = 29$). Users reported Device C being significantly easier to mount ($t = 3.10$, $p = 0.002$, $df = 29$). The reported speed of mounting was significantly faster for device C ($t = 3.14$, $p = 0.001$, $df = 29$). The responses to both the CRS ($t = 6.38$, $p = 0.000$, $df = 29$) and WEAR ($t = 4.72$, $p = 0.000$, $df = 29$) scales were significantly higher for device C than device D. Based on the statistical analysis device C, was significantly better than device D,

therefore the goal to create a new device that would increase social acceptability and usability for women was attained.

6.3.9 Future Work

During this comparative analysis the three new prototypes significantly outperformed the baseline OpenBCI headset. This could have been a result of the design of the baseline headset. Many participants reported the headset as being socially unacceptable and being unwilling to wear it during their post interview. The task completion time difference was likely a result of the fit of the headset. Because the headset is made of rigid 3D printed material, it did not fit well on many of the participants' heads. In addition to being ill fitting, some users reported discomfort over time. As the device shifted on participants' head, the signal quality could have decreased or the discomfort could have been a distraction from the engagement task. Although this headset was chosen as a good baseline because of its ability to allow for consistent data capture across both studies, future work would be to compare prototypes A,B, and C to existing wearable BCI devices such as the Muse and the Insight.

Additionally, there is no easy way to compare signal quality across devices. Because each device manufacturer has their own methods for calculating and reporting signal quality, cross device comparison is not currently done. More work to investigate methods of comparison need to done. Although a validated method of comparison does not exist, an attempt to examine the signal quality of the prototype headbands to an existing device was made. Because the task done in this usability study was the same task done previously for the qualifying rounds of the Brain-Drone Race, average task completion times from both participant groups were compared as a cursory check for

signal comparison between the Emotiv Insight Device and the prototype headsets. The average task completion time for the Brain-Drone Race was approximately 18 seconds (σ=19.08) while the task completions times for the prototypes were all around 24 seconds ($\sigma \approx 2$).

CHAPTER 7
SUMMARY AND FUTURE DIRECTIONS

7.1 Design Trade-off Conclusions and Future Work

Throughout this study, variations in design considerations were an underlying theme. The intention was to have a better understanding of the factors that affect user satisfaction, willingness to wear, and women's ability to use as it pertains to BCI. This research could not evaluate every possible variation of BCI device design, but it sets up a framework for future consideration as well as offers commentary based on observations and results from a series of studies. Future BCI researchers and designers can not only reference this as a tool in their early stages of planning but can contribute their observations and research findings. This section summarizes the findings from this body of work organized as design decisions and tradeoffs.

When creating a BCI device, there are several design factors to consider that can be categorized by two overarching theme;

- Form Factor (Headband, Cap, Material)
- Sensors (Placement, Type, Number)

These factors can affect performance and overall user experience. The factors determine if hair will be an issue, the type of styles the hair must be worn in, and if various textures will degrade the performance. Finally, the factors can dictate what the EEG data is being used to do.

Form factor: The form factor is important because it can dictate the decision for all the remaining factors. BCI devices come in various forms. The most common are electrode caps and uniquely shaped plastic hardware. Findings from this research suggest that the most socially acceptable BCI devices come in the form of existing headgear and accessories. Currently, EEG embedded helmets, hats, and headphones

are gaining more traction in the field. This project introduced the traditional headband and more fashion conscious forehead headband.

Traditional headband: A traditional headband design requires the use of in-scalp sensors. In scalp sensors should be optimized for hair penetration. With the correct sensors, the traditional headband can work with various hair textures and styles. However, it could limit the user from wearing some styles that involve wearing their hair in their face. During this study there was not significant difference between the performance of the traditional headband and the forehead headband. However, due to the limited about of space for sensors, this device would not be recommended when a medical grade device is needed. This device is recommended for more casual tasks involving frontal lobe data collection. This form factor was considered socially acceptable and has an overall positive user experience. If user experience is important, and there is a desire to work with thick or course hair, while using in scalp sensors, the traditional headband is a good option. However, if medical grade data collection is needed or data collection from brain regions not found near the front is needed, this form factor is not appropriate.

Forehead headband: The forehead headbands used in this study did not interfere with users' hair. Although a forehead headband could have sensors placed in the rear near the occipital lobe, the original intention was for forehead sensor placement. Devices like the Muse currently work well with various hair styles and textures, because it avoids in scalp sensors. However, specific haircuts around the face, such as bangs can interfere with a user's perception of the device. If the sensors are only placed on the forehead, flat sensors are recommended. User's responded

positively to the conductive ink used for the Muse's sensors. In general the Muse device received the most positive feedback during focus groups, and the forehead headband design was the preferred device for women during the second usability study. There were no significant differences in performance between the traditional headband and forehead headband designs in this study. Again, due to the limited about of space for sensors, this device would not be recommended when a medical grade device is needed. This device is recommended for more casual tasks involving frontal lobe data collection. However, with the appropriate additional sensors and placement of the headband, data could be collected from the parietal or occipital lobes. If user experience is important, and there is a desire to avoid user's hair, the forehead headband is an ideal option.

Electrode caps: Electrode caps are still the preferred method for medical grade EEG data collection and research. Some researchers in the field have yet to accept more wearable like devices with fewer sensors as being comparable to full EEG electrode caps. Many EEG caps still utilize wet electrodes as well. During the focus groups 100% of the participants reported being unwilling to wear any device that required wet electrodes. However, some companies like g.Tec have medical grade electrode caps with dry sensors (G.tec, 2012). The OpenBCI headset used in the first usability study is considered to have medical grade capabilities when the full 16-channel system is utilized. Although electrode caps are preferred by researchers who use BCI to do medical research, they are not the best for user experience or frequent usage by healthy users. These devices not only hinder the hairstyles that can be worn, but they do not often work well for all hair textures and densities. However, G.tec now has a

comb-like sensor for their systems that can help with the penetration of various hair textures. Because these caps, span the entire head, they can be used to capture EEG data from any of the brains regions. With the comb like sensors and chin strap to hold the cap on, some EEG caps are able to work effectively for a wide range of people. When considering people with less dense or little to no hair, EEG caps are good for high performance medical research where UX is not a critical concern.

Sensor placement: There are two key considerations when determining sensor placement. The first consideration is for the type of EEG data being collected. What is the goal or purpose of the data collection? That determines the region of the brain the sensors should ideally be located near. Most BCI devices' sensors are placed in accordance with the 10-20 system (American Electroencephalographic Society, 1994).

The second consideration is hair interference. Hair interference can lead to an inability for some people to use BCI. Therefore, when designing a device, a plan for hair circumvention must be determined. Either avoid the hair through the use of forehead sensors or penetrate the hair through the use of comb-like sensors.

Sensor type: Many companies have patent pending processes for the materials used to create their EEG sensors. Emotiv EPOC used wet electrodes that utilized felt pads while the Emotiv Insight uses a proprietary silicon based material for the sensors. The Muse's sensors are conductive ink printed onto the device. Other devices place the metals parts directly onto users' skin. This study did not evaluate every possible type of sensor. However, for the purpose of this research, sensor type was categorized as dry or wet and flat or comb-like. It is not recommended to use wet sensor for wearable BCI devices intended to be used by healthy users for non-research purposes. It was

uncovered during the focus groups, that women are not willing to wear devices that require wet electrodes regularly if at all. Flat sensors are recommended for use in locations where hair is not an issue such as the forehead or behind the ears. It is of interest to note that conductive ink design used by Muse was well received by participants. Finally, comb-sensors should be used for in-scalp data collection.

Sensor count: The number of sensors on a device can vary from 1-64 typically for wireless solutions. Most medical grade EEG devices have at least eight sensors. However, the Insight has five EEG sensors and the Muse has four EEG sensors. They are both popular consumer grade devices. The desired measurement can determine the number of appropriate sensors. For example, relaxation or engagement can be measured with one or two sensors, but it can be difficult to draw more in-depth conclusions for larger scale research goals from two regionally located sensor. It may be more appropriate to have a larger number of sensors spread out across the head (iMotions, 2016).

Limitations: This list of design tradeoffs is not an exhaustive list. It is based on field observations, experience with the research community, and insights of this body of work. This work focused on the design and evaluation of wireless wearable consumer grade EEG devices. Therefore considerations for variations in medical grade and wired EEG devices were not made. This research consisted of 2 focus groups, with 20 participants and 10 participants, as well as two usability studies each with 30 participants. Although feedback was generally consistent among this sample size and saturation was reached, a larger scale survey could be used to reach more people and gather more qualitative feedback. Finally, this research focused on woman as a target

user group, therefore, the suggestions and trade-off analysis specifically refer to that user group’s needs and have not been tested with male subjects.

7.2 Conclusion

The goal of this research was to use a female-driven UCD process to create three more socially acceptable BCI devices and to improve usability for women. In addition to the devices, a list of characteristics of socially acceptable BCI devices was developed to contribute to the wearable and BCI communities. All of these goals were achieved. Usability testing was done to compare the effectiveness, efficiency, and satisfaction of the three prototypes against an existing device. The three prototypes all outperformed the existing device in usability testing. In addition to the usability metrics, user preference among the prototypes was examined for future work. When considering new technology and its success, there are three main considerations; usability, usefulness and if it is used. This work sought to target the usability aspects and to create devices that women would use. This was seen as a priority because as new useful applications emerge, women will not benefit if the devices are not desirable or usable.

7.2.1 Limitations

Throughout this process there were a few limitations to take note of for similar work in the future. During the first usability study, it was decided to not use all 8 electrodes for the drone task. Using only the forehead sensors may have led to a false level of confidence in the mounting/setup process. If participants were forced to sit through the set up of getting eight electrodes connected and having good scalp contact, the feedback may have been different. Additionally, some participants would not have been able to participate.

The second usability study was not performed in the same location as the first usability study, due to the relocation of the researcher. However, every attempt was made to keep the experiment as consistent as possible across both studies. Additionally, the first usability study and both focus groups took place on a university campus, while the second usability study did not. This is believed to have had very little effect on the outcome. The final design decisions were highly influenced by feedback from the focus groups, and they performed well on all the metrics when tested with the non-university participants.

There were also engineering constraints and limitations during the fabrication phase. This work was sponsored by the Intel Corporation and the original agreement was for the company to assist with the device fabrication. Because this did not happen, the fidelity of the prototypes diminished from what was originally planned. However, the lower fidelity prototypes along with the image rich one-pager were able to accurately communicate the ideas to participants. The low level fidelity of the prototypes opened the door for future work.

7.2.2 Future Work

Due to the exploratory nature of the beginning phases of this research, very rich qualitative feedback was uncovered, all of which could not be explored for this project. Future projects could continue the exploration of the qualitative investigation into socially acceptable head worn wearables, which is a broader scope than this work that focuses on BCI. Specially, investigating how this list of 32 characteristics can be applied to the development of other wearables that are worn on the head and that are not would be an open area to explore. Continuing work to refine the list of 32 characteristics and

possibly creating a standardized scale to evaluate social acceptability of BCI is also an open area because such a tool does not exist.

Continuing work to add to and further substantiate the design trade off taxonomy is an additional future step. The creation of a document or open source website that can be shared and edited by the community is a future goal.

Finally, taking the users feedback and device preferences to make a higher fidelity prototype of device B, to be feature tested and productize is a clear next step. The first challenge to be addressed is the need for a versatile clipping mechanism to attach the sensor plate to various headgear if the elastic headband idea is abandoned.

This mix-method research successfully used qualitative and quantitative methods to address and improve social acceptability and usability of BCI devices for women. This work will enable and empower women to use EEG technology as more innovative application solutions become available. This will be particularly useful in education, person informatics and health in the near future.

APPENDIX A
SURVEY INSTRUMENTS

A.1 Pre-Survey

1. Age:

2. Do you self-identify as a woman?

3. How do you describe yourself?

    a. American Indian or Alaska Native
    b. Hawaiian or other Pacific Islander
    c. Asian or Asian American
    d. Black or African American
    e. Hispanic or Latino
    f. Non-Hispanic White
    g. Other ____________

4. Major:

5. Do you own any wearable device (excluding a mobile phone)?

    a. If so please list in order or usage:

6. How many days a week do you wear wearable devices (1-7)?

7. What is/are the primary purpose(s) of the device(s) you use?

    a. Fitness
    b. Mobile phone replacement/supplement
    c. Basic Clock
    d. Safety
    e. Non-fitness life-logging (i.e. sleep or other biometric data)
    f. Other __________________

A2. CRS Scale

Rate your level of agreement with the following statements:

1. I am worried about how I look when I wear this device. I feel tense or on edge because I am wearing the device.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

2. I can feel the device on my body. I can feel the device moving.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

3. The device is causing me some harm. The device is painful to wear.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

4. Wearing the device makes me feel physically different. I feel strange wearing the device.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

5. The device affects the way I move. The device inhibits or restricts my movement.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

6. I do not feel secure wearing the device.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Low High

A3. WEAR Scale

To what extent do you agree or disagree with the following statements?

1. **I like what this device communicates about its wearer.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

2. **I could imagine aspiring to be like the wearer of such a device.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

3. **This device is consistent with my self-image.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

4. **This device would enhance the wearer's image.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

5. **The wearer of this device would get a positive reaction from others.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

6. **I like how this device shows membership to a certain social group.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

7. **This device seems to be useful and easy to use.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

8. **This device could help people.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

9. **This device could allow its wearer to take advantage of people.**

   Strongly Agree Agree Neutral Disagree Strongly Disagree

10. **Use of this device raises privacy issues.**

    Strongly Agree Agree Neutral Disagree Strongly Disagree

11. The wearer of this device could be considered rude.

Strongly Agree Agree Neutral Disagree Strongly Disagree

12. Wearing this device could be considered inappropriate.

Strongly Agree Agree Neutral Disagree Strongly Disagree

13. People would not be offended by the wearing of this device.

Strongly Agree Agree Neutral Disagree Strongly Disagree

14. This device would be distracting when driving.

Strongly Agree Agree Neutral Disagree Strongly Disagree

A4. Custom Post Survey Questions

Additional Questions:

1. How likely are you to wear this device in public?

Very Unlikely Unlikely Neutral Likely Very Likely

2. How socially acceptable is the device?

Very Unacceptable Unacceptable Neutral Acceptable Very Acceptable

3. How comfortable was this device to wear?

Very Uncomfortable Uncomfortable Neutral Comfortable Very Comfortable

4. How easy was this device to setup?

Very Difficult Difficult Neutral Easy Very Easy

5. How was the speed of setup for this device

Very Slow Slow Neutral Fast Very Fast

A5. Post Interview Questions (Study I)

1. What do you think about the device?
2. How likely are you to wear this device in public?
3. How socially acceptable would you say this device is?
4. Any additional comments?

A6. Post Interview Questions (Study II)

Following EACH device:

Additional Verbal Questions:

1. How likely are you to wear this device in public?
    1. Would you consider it socially acceptable?
    2. Do you think it would inhibit your outfit or hairstyle?
2. How comfortable was this device to wear?
3. How easy was this device to setup, would you be willing to do this regularly?
4. How was the speed of setup for this device
5. General Feedback?

Following ALL devices

Verbal

1. What do you think about the devices?
2. Rank the devices in order of preference or likeliness to wear.
3. Any additional comments?

APPENDIX B
PROTOTYPE FABRICATION PHOTOS

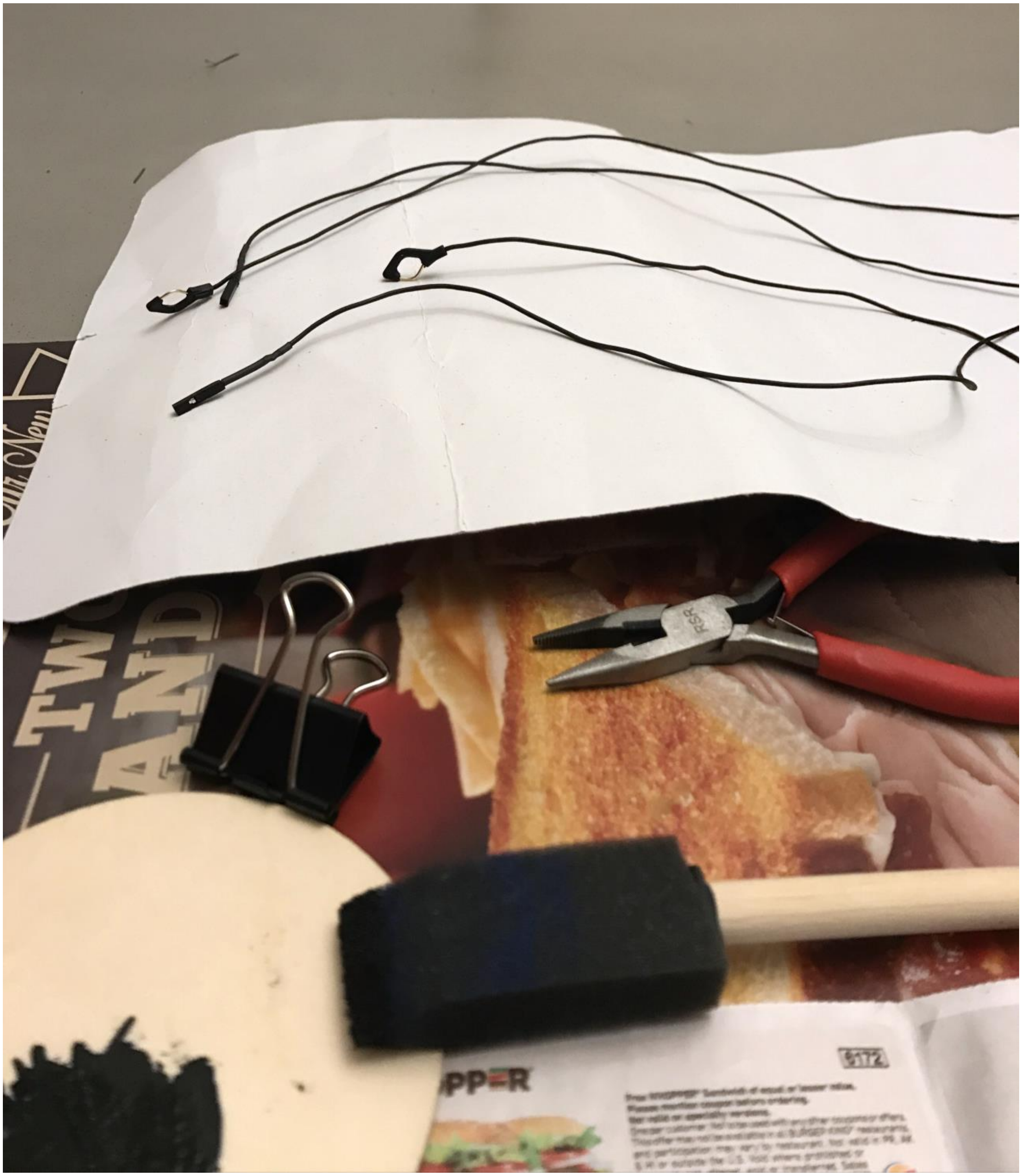

Figure B-1. Lead wires being painted with black acrylic paint (Photo courtesy of the author)

Figure B-2. Sensor placements being marked the traditional headband (Photo courtesy of the author)

Figure B-3. Inside the foam sensor housing for the transferable sensor plate (Photo courtesy of the author)

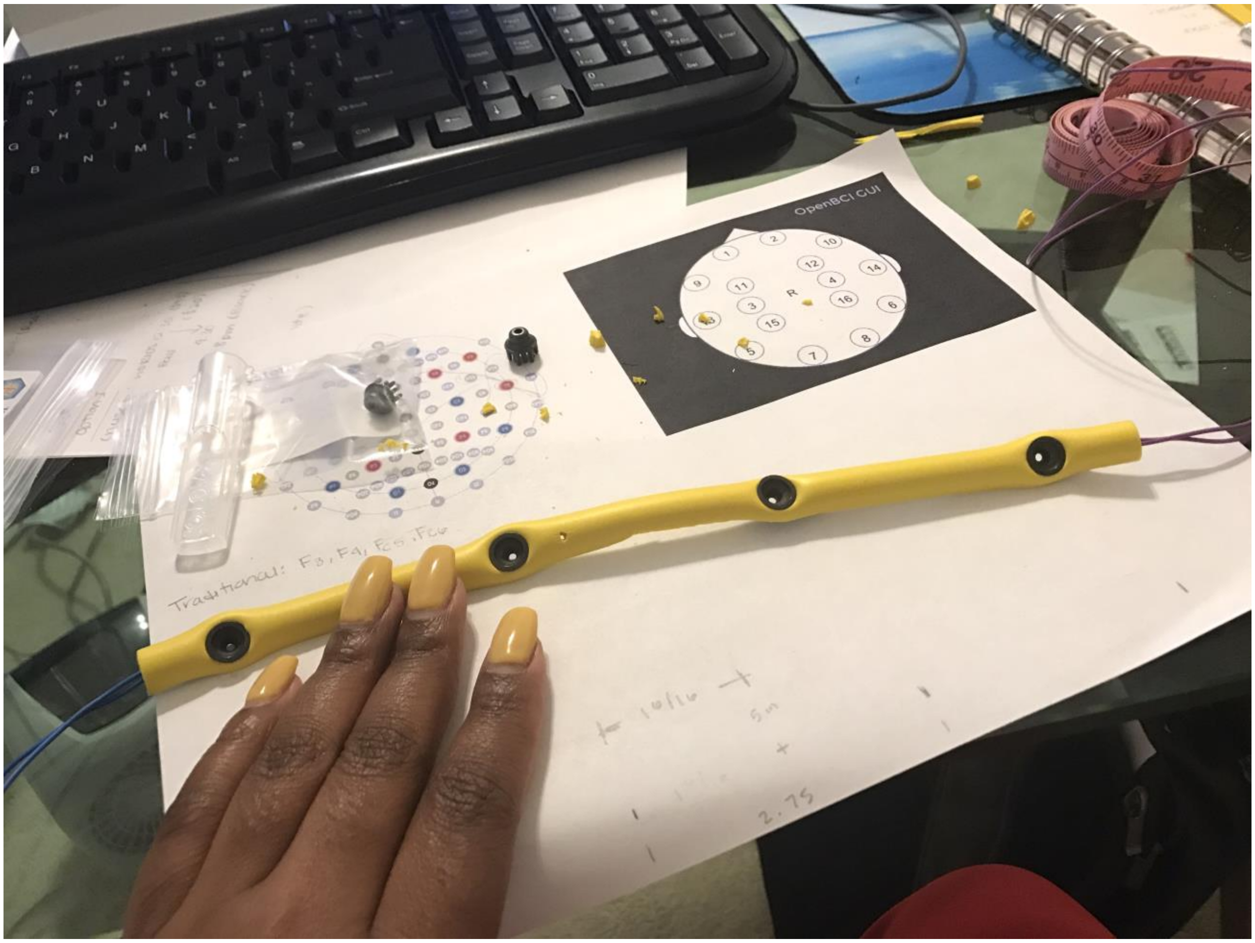

Figure B-4. Foam sensor housing for the transferable sensor plate (Photo courtesy of the author)

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